Institutul Naţional de Cercetare Dezvoltare pentru Fizică şi Inginerie Nucleară Horia Hulubei

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Nr ieşire contractor IFIN-HH ………/……. Nr. intrare IFA ………../……

**FIŞĂ DE DEPUNERE DOCUMENTE**

Către,

**Autoritatea contractantă: INSTITUTUL DE FIZICĂ ATOMICĂ - IFA**
**Acronim proiect: NAIRIB**
**Contract nr: 02 FAIR / 16.09.2016**

**Institutul de Fizica si Inginerie Nucleara "Horia Hulubei",** în calitate de conducător al proiectului: *„Nuclear Astrophysics with Indirect-methods and Rare Ion Beams/NAIRIB"* vă transmitem anexat următoarele documente (se bifează documentele anexate):

- ☐ Act adiţional nr……....
- ☐ Cerea de plată avans
- ☐ Cererea de plată intermediară
- ☐ Cererea de plată finală
- ☒ **Raportul intermediar de activitate 4r. r. 4**
- ☐ **Raportul final de activitate**

**Director proiect,**

**Dr. Livius Trache**

Livius Trache IFIN

Digitally signed by Livius Trache IFIN
DN: cn=Livius Trache IFIN, o=IFIN-HH, ou, email=livius.trache@nipne.ro, c=RO
Date: 2019.11.23 16:21:14 +02'00'

**RAPORT INTERMEDIAR/FINAL DE ACTIVITATE NR.* 4**

| | |
|---|---|
| Denumirea proiectului | *Nuclear Astrophysics with Indirect-methods and Rare Ion Beams/NAIRIB* |
| Număr de contract | 02 FAIR |
| Conducător de proiect | Institutul de Fizica si Inginerie Nucleara "Horia Hulubei" |
| Perioada raportată | 01.01.2019-15.12.2019 |
| Număr total de pagini | |

*****Numărul raportului intermediar va coincide cu nr. etapei/fazei de execuţie. Nu se atribuie niciun număr raportului final.

Raportul conține Secțiunea 1 – ***Raport științific intermediar nr. 4*** și Secțiunea 2 – ***Raport explicativ al cheltuielilor***. (La predare, Raportul se prezintă și pe suport electronic.)

Subsemnatul Nicolae Victor Zamfir în calitate de reprezentant legal autorizat al Institutul de Fizica si Inginerie Nucleara "Horia Hulubei" declar, pe proprie răspundere, că datele furnizate prin prezentul Raport de activitate sunt reale şi că toate cheltuielile s-au efectuat în mod exclusiv pentru realizarea şi în conformitate cu prevederile contractului nr 02 FAIR/16.09.2016 finanţat prin PN III/Programul 5/Subprogramul 5.2/Modulul FAIR-RO

Reprezentant legal al
Conducatorului de proiect,
Director General
Acad. Nicolae Victor Zamfir

Director Proiect,
Dr. Livius Trache

Director Economic,
Ec. Alexandru Popescu

Data: 28 Nov. 2019

**Secțiunea 1 – Raport științific intermediar**

# RAPORT ŞTIINŢIFIC INTERMEDIAR

**ETAPA DE EXECUŢIE NR. 4/ 4th EXECUTION PHASE**

**CU TITLUL**
**IV.1 "Evaluare factori S astrofizici pentru reactii de captura radiativa a protonilor la energii stelare"**

**(Title:**
**IV.1 " Evaluation of astrophysical S-factors for radiative proton capture reactions at stellar energies")**

Project: PNIII/P5/P5.2 nr. 02/FAIR-RO

**Project title: "Nuclear Astrophysics with Indirect-methods and Rare Ion Beams/ NAIRIB"**

**Intermediate report nr. 14 November 2019**

Consideram ca obiectivele acestei faze au fost integral indeplinite.

Project director
Dr. Livius Trache

Livius Trache
IFIN

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**Annual Summary Document**

Project: PNIII/P5/P5.2 nr. 02/FAIR-RO

**Project title: "Nuclear Astrophysics with Indirect-methods and Rare Ion Beams/ NAIRIB"**

4th intermediate report – Jan- Dec 2019
**"Evaluation of astrophysical S-factors for radiative proton capture reactions from indirect data"**

# 1. Cover Page

- **Group list (physicists, staff, postdocs, students);**
  The project team was composed by the following members:
  1. Livius TRACHE, Project Director, CS I
  2. Florin CARSTOIU, senior researcher, CS I
  3. Alexandra SPIRIDON, PhD, Research Scientist
  4. Alexandra-Ionela CHILUG, PhD student, Research Assistant
  5. Dana TUDOR, PhD student, Research Assistant
  6. Ionut-Catalin STEFANESCU, PhD student, Research Assistant
  7. Iuliana STANCIU, PhD student, Research Assistant
  8. Valentin BALANICA, Physicist

- **Specific scientific focus of group**

The focus of the Nuclear Astrophysics Group (NAG) at the Department of Nuclear Physics (DFN) from IFIN-HH is **nuclear physics for astrophysics**. While the group is using also direct measurements, the use of **indirect methods with radioactive beams for nuclear astrophysics** is mostly funded through this project.

So far different radiative proton capture reactions were our focus. During the period covered by this grant we conducted experiments using:

- **nuclear and Coulomb proton breakup of $^{9}$C→ $^{8}$B + p** to determine astrophysical reaction rates for the reaction $^{8}$B(p,γ)$^{9}$C
- **resonance spectroscopy** for the reactions $^{30}$P(p,γ)$^{31}$S and $^{26}$Al(p,γ)$^{27}$Si. We studied the spectroscopy of $^{31}$S and $^{27}$Si through the **beta-delayed proton-decay of $^{31}$Cl and $^{27}$P**.

In addition, NAG or its members participated in national and international activities - experiments, data analyses or meetings - related to the topic of this grant: nuclear astrophysics.

### Summary of accomplishments during the reporting period

1) The experiment NP1412-SAMURAI29R1 on the breakup of $^{9}$C, proposed and approved by RIBF PAC in Dec. 2014, was carried out at RIKEN, Wako, in Japan, between June 1-3, 2018. Alexandra Chilug works on the complex **data analysis** of the two experiments - nuclear and Coulomb breakup of $^{9}$C - its **framework is well set**.
2) Early efforts to carry out indirect measurements using the Trojan Horse method for the $^{12}$C+$^{12}$C reaction, was published in the prestigious journal ***Nature*** in May 2018 [1]. Two NAG scientists participated when these efforts were complemented by **two other**

**very recent experiments in Oct. – Nov. 2019, at the tandem accelerator of LNS Catania**.

3) The experiment proposed for the study of the **beta-delayed proton-decay of $^{27}$P** accepted last year by our partners and the management at the Cyclotron Institute, Texas A&M University, was carried out very recently: on Nov. 25 – Dec. 5, 2019.
4) The Project Director and prof. A. Petrovici at the request of RIKEN have intermediated a **Collaboration Agreement signed between RIKEN, Japan and the Doctoral School of Physics of the University of Bucharest.** IFIN-HH is part of the Doctoral School of Physics of UB. Two of my students, Alexandra Chilug and Ionut Stefanescu have obtained fellowships as International Program Associates of RIKEN for one year and six months respectively, beginning Nov. 1, 2019 and are working now at the Nishina Center in Wako, Japan.
5) The **Proceedings of the Carpathian Summer School of Physics 2018** was completed in the first part of 2019 and was published at the American Institute of Physics:
   Livius Trache and Alexandra Spiridon (eds.), **"Exotic Nuclei and Nuclear/Particle Astrophysics (VII). Physics with small accelerators",** AIP Conference Proceedings, vol. **2076**, NY 2019.
6) The fifth edition of the (national) **Summer School for Physics Olympics**, July 16-23, 2019 was successfully organized again in Busteni in collaboration with the NGO Apex-Edu from Cluj-Napoca.
7) For the publications of the group and conference talks – see later section of this report.
8) **Two new proposals** were submitted to the IFIN-HH PAC session of Nov. 10-11, 2019. Both were approved.
9) **Two new proposals for international events in 2020** were submitted and approved:
   a. A new edition of a **training school** “A hands-on experiment in nuclear astrophysics at IFIN-HH” was approved by the ChETEC CA 16117 Management Committee for April 2020.
   b. An **ECT* workshop** “Key Reactions in Nuclear Astrophysics” with the PD as co-organizer was submitted and approved by the ETC* scientific board for June 22-26, 2020. The workshop is organized by the same group of 5 scientists from 5 countries and 3 continents that have successfully organized the ECT* workshop of Nov. 2018 (see the 2018 report).

## 2. Scientific accomplishments

This report combines the organizational, personnel, financial and scientific aspects of our work in the current year (2019) under this project. In many cases a clear separation between work under this project and other projects or sources of financing is not possible, and I will mention those specifically, where possible.

In 2019 the project team was essentially the same as for the 2018 part of this project. The positions of some of the young members of the group have changed:

- Alexandra Chilug and Ionut Stefanescu have obtained fellowships as International Program Associates of RIKEN for one year and six months respectively, beginning Nov. 1, 2019 and are working now at the Nishina Center in Wako, Japan. They remain members of NAG.
- Dana Tudor, married State, has become the mother of a young boy, Tudor, and is on maternity leave beginning Aug. 20, 2029.

- The appointments in IFIN-HH of all 3 above have been extended for 2020.

NAG continued to work in 2018 in nuclear physics for astrophysics (NPA) **research** and **education and formation.** These were stated in the original proposal as:

a) Work at existing RIB facilities, to test the methods, setups and theories involved
b) Design and realization of experimental setups
c) Not in the last and least, the training of young group members

**Research** (items a) and b) above) concentrated on (1) the use of **direct measurements** for nuclear astrophysics, conducted at IFIN-HH facilities but not financed by this project and (2) on the use of **indirect methods** with experiments carried out at international facilities and financed mostly through this project. Group's activities remained closely intertwined, with their goals well and consistently followed through. The most important achievement of the year was for sure the successful experiment on beta-delayed proton-decay of $^{27}$P which was conducted recently (Nov. 25 - Dec. 5, 2019) at Texas A&M University. Another is the advance of ASTROBOX2E.

**Education and formation** (item c) were also in the focus of the project director (PD) of this project and of the group (as per its proposal) and consisted of the continuous formation of its younger members, as well as from activities targeting a broader, international audience. The younger members were or are part in PhD programs, 3 at the Physics Doctoral School of the University of Bucharest and 1 at a foreign university (TU München, Germany).

- The younger members of the group were consistently advised and prepared to participate to international events on nuclear astrophysics. In addition to funds from this grant and from the grant NUCASTRO2 (PNIII-P4-ID-PCE-2016-0743), we could use European funds from the COST action CA16117 ChETEC for five such participations. In each one of these cases they were presenting communications.
- Three of the four PhD students have thesis subjects related to experiments at prestigious international laboratories in Japan, USA and Germany. They all travelled there for work. In two cases, the host laboratories have supported the costs, a sign of appreciation of their contributions. All three have obtained stipends for longer periods of time at RIKEN, Japan (A. Chilug and I. Stefanescu) and Technische Universitaet Muenchen (I. Stanciu), respectively.

As for the broader audience, the PD has organized, with the help of NAG members,

- The fifth edition of the (national) Summer School for Physics Olympics, July 16-23, 2019 was organized again in Busteni in collaboration with the NGO Apex-Edu from Cluj-Napoca. This edition of the event was well appreciated by the about 20 high school students, best in their senior classes, selected from the finalists of the Romanian Physics Olympiads. In addition to the PD who is the director of the scientific part of these schools, two young members of NAG were lecturing in Busteni. Dr. Alexandra Spiridon was talking about her experience as PhD student in USA, while drd. Alexandra Chilug was talking about her thesis work in IFIN-HH, centred on an experiment we had at RIBF RIKEN in Wako, Japan.

At this section on formation of the new generations of scientists I should include that one group member has proposed (Oct. 2019) a project in the new UEFISCDI competition for

Post-Doctoral grants on the study of ion-ion fusion mechanism and that the NAG youngsters have 4 local beamtime proposals approved by PAC and one external proposal accepted at Texas A&M University.

Note that none of these events were directly financed from this NAIRIB project (except for the partial support for the participation of some group members to some of them), because funds were not available or came from other sources, but they cannot be separated from the activities of the group in the research direction financed by it. They were in the research area financed by this project (and its sister project NUCASTRO2 of UEFISCDI), and, as we said before, we both made efforts and benefited from them and as such they cannot be ignored in this report.

## 2.1 Data evaluation of RIBF RIKEN experiment NP1412-SAMURAI29R1

The year 2018 for the NAG group was dominated by two major experiments – one at RIBF RIKEN, Japan and one at IFIN-HH's own tandem accelerator –and by 3 large international events that we have organized, two in Romania and one in Trento, Italy. During 2019, therefore, we had to concentrate in finalizing what we started before and on preparing the immediate future, including preliminary experiments at the 3 MV tandetron in Bucharest. Chiefly among these activities, was the data analysis I will only refer briefly to the first one, of the NP1412-SAMURAI29R1 experiment. The spectroscopy experiment at the 9 MV tandem of IFIN-HH is in too early of stages to be described here in detail.
The experiment SAMURAI29R1 was proposed and approved by RIBF PAC in Dec. 2014. and then actually carried on, June 6-8, 2018 with the participation of the whole group.

The motivation for it is to determine the astrophysical S-factor $S_{18}(0)$ for the radiative proton capture reaction $^{8}B(p,\gamma)^{9}C$ using both nuclear and Coulomb breakup (two different and complementary methods).

The setup and the experiment were described in detail in past years' reports. The data analysis is under way, but not completed and I shall not further discuss this topic here. Of valuable importance for the success of the analysis will be the support from profs. Tohru Motobayashi and Tomohiro Uesaka during our students stays at the Nishina Center, RIKEN. We are working with the theoreticians who are part of the project Florin Carstoiu (IFIN-HH), Carlos Bertulani (Texas A&M Commerce) and Angela Bonaccorso (INFN Pisa).

Short communications about the experiments were presented by my student Alexandra Chilug at CSSP18 (presentation of the simulations made in preparation of the experiment) and at the ECT* workshop on Indirect Methods in Nuclear Astrophysics, Trento, at the beginning of November. The $^{9}C$ breakup is a subject part of her thesis.
The communication selected for oral presentation at the Nucleus-Nucleus 2018 Conference held Dec. 4-8 in Omiya, Japan was prepared and approved for publication in the NN2018 Proceedings, in preparation at JPS Conf Series.
Drd. Alexandra Chilug was invited and supported by RIKEN at one new experiment at RIBF in its Spring 2019 experiment. The experiment is part of the set of four experiments dubbed “HI-p”, which use the Si-detector system developed by us with our US, Japan and Hungary collaborators, to be placed between the target and the SAMURAI spectrometer. The experiment was successful.

## 2.2 The $^{12}C$+$^{12}C$ reaction

***$^{12}C$+$^{12}C$*** is a crucial reaction in nuclear astrophysics, one of the most important. There are plenty attempts to measure or evaluate the fusion cross section for this reaction at low energies, which is dominated by resonances. Direct measurements and indirect methods are being used. The Nuclear Astrophysics Group (NAG) at IFIN-HH participated in two of the most recent attempts:

- The study of an adjacent reaction: $^{13}C$+$^{12}C$ to evaluate the reaction mechanism at deep sub-barrier energies. This was a substantial joint effort with experiments at the 3 MV tandetron of IFIN-HH and de-activation measurements in our ultra-low background laboratory in the Slănic-Prahova salt mine. A paper was submitted to Phys. Lett. B in Sept 2019, by our collaborators at IMP Lanzhou, China, A separate paper prepared by NAG is in final evaluation steps at NIM A.
- The use of Trojan Horse Method (THM) to find the resonances involved, down to about $E_{cm}$=1 MeV, therefore covering the Gamow window for temperatures 1 GK and higher. This project lasted a few years and was led by our collaborators from LNS Catania, resulting in a publication in the journal Nature [A. Tumino et al. **Nature 557**, 687 (2018)]. The importance of the subject and of the publication convinced the collaboration to extend the experiment. This was done in Oct-Nov and Dec 2019, with our participation. I'll not elaborate on this topic here, but I will mention that these results brought us to the conclusion to continue the studies of similar reactions, using THM in Catania and the ion-ion fusion at sub-Coulomb energies in Bucharest.

## 2.3 The ASTROBOX2 experiment at Texas A&M University

The success in building and commissioning the ASTROBOX2 detector capable to measure very low-energy protons following beta-delayed proton-decay of exotic nuclei at the MARS separator of the Cyclotron Institute, Texas A&M University allowed us to propose an experiment to measure the decay of $^{27}P$. We had this experiment very recently Nov. 25 – Dec. 5, 2019 in College Station.

## 2.4. Evaluation of astrophysical S-factors for radiative proton capture reactions from indirect data

This is the title topic of this last year (2019) of the NAIRIB project. The goal of all studies of nuclear physics for astrophysics is to determine or evaluate the reaction cross sections, equivalently the astrophysical S-factors, at the very low energies important in the stars. Radiative proton capture reactions is one of the most frequent class of reactions in stars and they all have a number of common characteristics and problems, when one attempts to measure them experimentally and/or evaluate them using theories. Instead of direct measurement, indirect methods are frequently used. I treated this topic in a paper that I attach to this report. The paper follows the lines of project director's talk at the opening of the ECT* workshop "Indirect Methods in Nuclear Astrophysics", Trento, Italy, Nov. 5-9, 2018. We briefly described the workshop in last year's report. The paper was written in June-July 2019. In a slightly modified form will be published as a review article in the journal ***SCIENCE CHINA** Physics, Mechanics & Astronomy* at the request of its Editors. It was posted on arXiv at http://arxiv.org/abs/1911.06077.

I copy in here only an introductory part that sets the main ideas on how to *connect the quantities measured with indirect methods to astrophysical S-factors*. They mostly refer to *radiative proton capture reactions.* More details are kept for the paper quoted above, included here and integral part of the report.

## Indirect Methods in Nuclear Astrophysics. The list

Before going to make the list of the indirect methods for nuclear astrophysics (IMNA), we have to say that it has to be, by necessity, a personal view of the current list. The methods can be organized and certainly ordered differently than below. We would start by saying that the first indirect nuclear data that were used for astrophysics were the mass measurements of the early XX-th century. Those measurements and the $E=mc^2$ of A. Einstein lead Sir A. Edington to suppose that solar energy arises from nuclear reactions. Further, the beta-decay studies allowed Critchfield and Bethe to propose and evaluate the pp-chain of reactions [2]. Then the lack of knowledge on the mass gaps at A=5 and A=8 lead to the wrong, but historically important, model of nucleosynthesis by Alpher, Bethe and Gamow published on April 1, 1948 [3]. And one could go on and on!

However, explicit proposals for indirect methods in nuclear astrophysics started gaining momentum in the mid-eighties of last century.

The list of IMNA, as presented and discussed at the workshop is:

A. Coulomb Dissociation
B. Single-nucleon transfer reactions – the ANC method
C. Nuclear breakup reactions
D. The Trojan Horse Method
E. Spectroscopy of resonances, a wide category of reactions, types of experiments and theories.

While it is clear that the indirect methods in the list above may differ from one another by laboratory energies at which they are applied and by the techniques used, both experimental and theoretical, there is a common path from their results to the evaluation of the cross sections or reaction rates at energies or temperatures relevant in stellar processes:

1. Experiments are made at energies usual for the nuclear physics laboratories
2. Theoretical (reaction) calculations are made
3. The experimental results of step (1) are compared with calculations of step (2) to extract nuclear information (typically nuclear structure parameters)
4. The extracted information is used to evaluate nuclear astrophysics data: cross sections, astrophysical S-factors or reaction rates.

These steps are also sketched in Figure 1. There (B on the right-hand side) a point is also made to show that in both steps 2 and 4, additional knowledge is very important. The theories and the parameters used in both situations, at large and at low energies, need to be well established and vetted throughout in order to give confidence on the end results. We should stress that most of the time it is important to have good, reliable calculations of the absolute values at point (2), a feature not exactly common to nuclear reaction theories. Another point that is not figured there and not specified above is the importance of the choice of the data/information that we extract at point (3), their relevance for the precision of the evaluation at step (4), and in particular the need that they are model independent, as much as possible. This will be exemplified when the ANC method will be discussed.

Another important step is to compare the results of the indirect methods (step 4) with results of direct measurements, if they exist (A, on the left side of the figure).

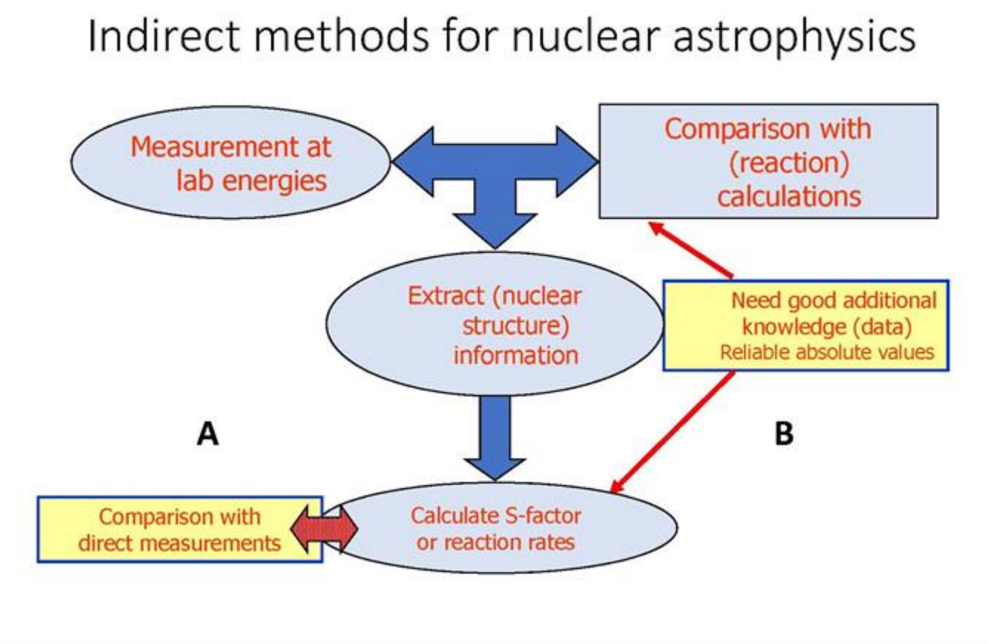


*Figure 1. The paradigm used in Indirect Methods in Nuclear Astrophysics.*


References:

[1] A. Tumino, … and L. Trache, *Nature*, **557**, 687 (2018).

[2] H.A. Bethe and C.L. Crichfield, *Phys. Rev*. **54**, 248( 1938).

[3] R. Alpher, H. Bethe. and G. Gamov, *Phys. Rev*. **73**, 803 (1948).


## 2.5 Proceedings of the Carpathian Summer School of Physics 2018

The **Carpathian Summer School of Physics 2018** (http://cssp18.nipne.ro/) was held July 1$^{st}$ - 14$^{th}$, 2018, in Sinaia, Romania. A full report was presented in last year's report. The **Proceedings of the Carpathian Summer School of Physics 2018** was completed in the first part of 2019 and was published at the American Institute of Physics:

Livius Trache and Alexandra Spiridon (eds.), **"Exotic Nuclei and Nuclear/Particle Astrophysics (VII). Physics with small accelerators",** AIP Conference Proceedings, vol. **2076**, NY 2019.

## 2.6 Future activities and events

At this chapter the proposals for future events in which the PD and NAG are the main organizers should be included:

- A proposal of a new edition of a training school "hands-on experiment in nuclear astrophysics at IFIN-HH" was approved the recent (Sep 18, 2019) meeting of ChETEC Management Committee for April 2020. The event will be fully financed by COST.

- Accordingly, a beamtime proposal was submitted to the PAC of Nov. 2019. The experiment was approved with maximum priority: 7 days of beamtime at the 3 MV tandetron.
- An ECT* workshop “Key Reactions in Nuclear Astrophysics” (the PD as co-organizer) was submitted and was approved by the ETC* scientific board for June 22-26, 2020. The workshop is organized by the same group of 5 scientists from 5 countries and 3 continents that have successfully organized the ECT* workshop of Nov. 2018 (see the 2018 report).
- A new experiment proposal was submitted and approved by the Nov. 2019 session of the IFIN-HH PAC. The subject is the study of ion-ion fusion reactions at low energies.
- The 2020 edition of the Carpathian Summer School of Physics is being prepared.

A proposal to extend the use of ASTROBOX2 for beta-delayed alpha-decay is contemplated.

## 3. Group members

Project NAIRIB

| Nr. | Name | Position in project | Professional rank | Profession | FTE |
|---|---|---|---|---|---|
| 1 | Livius TRACHE | Project Director | CS1 | physicist | 0.8 |
| 2 | Florin CARSTOIU | senior researcher | CS1 | physicist | 0.2 |
| 3 | Alexandra SPIRIDON | Team member | CS, PhD. | physicist | 1 |
| 4 | Alexandra CHILUG | Team member | AC | physicist | 1 |
| 5 | Dana TUDOR | Team member | AC | physicist | 1 |
| 6 | Ionut STEFANESCU | Team member | AC | physicist | 1 |
| 7 | Iuliana STANCIU | Team member | AC | physicist | 0.0 |
| 8 | Valentin BALANICA | Team member | physicist | physicist | 0.2 |
| 9 | Andreea SUVAILA | Team member | Ec. | economist | 0.0 |

AC = Research Assistant

CS1 = Senior Researcher 1

### Group members who are students:

Four students, all graduated their master studies and are PhD students now and during whole 2019 year:

1. Alexandra-Ionela CHILUG, PhD student, Research Assistant
2. Dana TUDOR, PhD student, Research Assistant
3. Ionut-Catalin STEFANESCU, PhD student, Research Assistant
4. Iuliana STANCIU, PhD student, Research Assistant

Physicist Valentin Balanica ceased his affiliation with IFIN-HH and, therefore, with this project, at the end of the first semester 2019.

As of Nov. 15, 2019

# 4. List of new publications and conference presentations

## 4.1 Publications

I include here papers published in 2019 (till Nov. 15) and papers shown on Web of Science webpage http://apps.webofknowledge.com as published after the previous year's report.

1. Alexandra Spiridon, Emmanuel Pollacco, Antti Saastamoinen, Robert E. Tribble, George Pascovici, Livius Trache, Bertrand Mehl, Rui de Oliveira, **Nuclear Inst. and Methods in Physics Research, A 943** (2019) 162461
   *A study in using MICROMEGAS to improve particle identification with the TAMU-MDM focal plane detector*
2. N. Zhang, … D. Tudor, A.I. Chilug, I.C. Stefanescu, M. Straticiuc, I. Burducea, D.G. Ghita, R. Margineanu, C. Gomoiu, A. Pantelica, D. Chesneanu, and L. Trache et al, submitted to **Phys Rev B,** Sept 2019.
   *Constraining the 12C+12C astrophysical S-factors with the 13C+12C measurements at very low energies*
3. Dana Tudor, A.I. Chilug, I.C. Stefanescu, A. Spiridon, M. Straticiuc, I. Burducea, L. Trache, R. Margineanu, in "Exotic Nuclei and Nuclear/Particle Astrophysics (VII). Physics with small accelerators", Proceedings CSSP18, AIP Conference Proceedings, vol. 2076, Melville, NY, 2019
   *Experimental study of the α+ 64Zn reaction in the Gamow region*
4. Alexandra Spiridon et al – in "Exotic Nuclei and Nuclear/Particle Astrophysics (VII). Physics with small accelerators", Proceedings CSSP18, AIP Conference Proceedings, vol. 2076, Melville, NY, 2019
   *Elastic studies with the upgraded TAMU-MDM detector*
5. Alexandra Chilug et al – in "Exotic Nuclei and Nuclear/Particle Astrophysics (VII). Physics with small accelerators", Proceedings CSSP18, AIP Conference Proceedings, vol. 2076, Melville, NY, 2019
   *Study of the $^{9}$C breakup through the NP1412-SAMURAI29R1 experiment*
6. Ionut Stefanescu – in "Exotic Nuclei and Nuclear/Particle Astrophysics (VII). Physics with small accelerators", Proceedings CSSP18, AIP Conference Proceedings, vol. 2076, Melville, NY, 2019
   *AstroBox2E: A detection system for very low energy beta-delayed proton decay*
7. A.I. Chilug et al. NN2018, , in *Proc. Nucleus-Nucleus Collisions 2018, Saitama, Dec. 2018*, **Jap Phys Soc Conf Ser**, accepted July 2019.
   *Nuclear Breakup and Coulomb Dissociation of 9C Nucleus Studied at RIBF RIKEN*
8. L. Stuhl et al., **Nuclear Inst. and Methods in Physics Research B**, 2019, accepted Sep. 2019, in press
   *Study of spin-isospin responses of radioactive nuclei with the background reduced neutron spectrometer, PANDORA*
9. A. Saastamoinen, E. Pollacco, B.T. Roeder, R. Chyzh, L. Trache, R.E. Tribble, **Nuclear Inst. and Methods in Physics Research B**, accepted May 2019, in press.
   *Studies of systematic effects of the AstroBox2 detector in online conditions.*
10. L. Trache, L. Lamia, R.G. Pizzone and M. LaCognata (eds.) Proc. ESSENA 2019, Eur. Phys. J. Conf. Ser., accepted Sept. 2019
    *Nuclear astrophysics studies at NIPNE*
11. D. Tudor, L. Trache, Alexandra I. Chilug, Ionut C. Stefanescu, Alexandra Spiridon, Mihai Straticiuc, Ion Burducea, Ana Pantelica, Romulus Margineanu, Dan G. Ghita,

Doru G. Pacesila, Radu F. Andrei, Claudia Gomoiu, Ning T. Zhang, Xiao D. Tang. Submitted to NIM A, June 26, 2019. https://arXiv:1909.07012
*A facility for direct measurements for nuclear astrophysics at IFIN-HH -- a 3 MV tandem accelerator and an ultra-low background laboratory*

12. A. Tumino, C. Spitaleri, M. La Cognata, S. Cherubini, L. Guardo, M. Gulino, S. Hayakawa, I. Indelicato, L. lamia, H. Petrascu, R.G. Pizzone, S.M.R. Puglia, G.G. Rapisarda, S. Romano, M.L. Serghi, R. Sparta and L. Trache, **Il Nuovo Cimento 42** C (2019) 55
*Uncovering carbon burning in stars*
13. Livius Trache and Florin Carstoiu, arXiv: http://arxiv.org/abs/1911.06077
*Indirect methods in Nuclear Astrophysics*

Books

1. **Livius Trache and Alexandra Spiridon (eds.)**, *Exotic nuclei and nuclear/particle astrophysics (VII) - Physics with small accelerators. Proceedings of the Carpathian Summer School of Physics 2018 (CSSP18).* Book Series: **American Institute of Physics Conference Proceedings**, Volume: 2076, Melville, New York, 2019.

   https://aip.scitation.org/toc/apc/2076/1?expanded=2076

We include pdf copies of articles 13, 1 and 7 at the end of the report, in Appendices.

## 4.2 Conference participations and presentations 2019

1. L. Trache, 16th Russbach School on Nuclear Astrophysics, in Russbach, Austria. March 10-16, 2019. Invited lecture *"Epilogue: the 3 ENNAS schools – past, present and future"*.
2. A. Spiridon, 16th Russbach School on Nuclear Astrophysics, in Russbach, Austria. March 10-16, 2019. Communication. Supported by ChETEC.
3. D. Tudor, 16th Russbach School on Nuclear Astrophysics, in Russbach, Austria. March 10-16, 2019. Communication. Supported by ChETEC.
4. I. Stefanescu, 16th Russbach School on Nuclear Astrophysics, in Russbach, Austria. March 10-16, 2019. Communication. Supported by ChETEC
5. I. Stanciu, 16th Russbach School on Nuclear Astrophysics, in Russbach, Austria. March 10-16, 2019. Communication. Supported by ChETEC
6. L. Trache, European Summer School on Experimental Nuclear Astrophysics 2019, June 16-23, Catania, Italy. Invited talk, *"Nuclear Astrophysics at IFIN-HH"*
7. A. Spiridon, European Summer School on Experimental Nuclear Astrophysics 2019, June 16-23, Catania, Italy. Communication. Supported by ChETEC
8. L. Trache, ChETEC Management Committee meeting (invited) and Nuclear Physics for Astrophysics IX, Sep. 15-20, 2019, Frankfurt, Germany. Supported by ChETEC.
9. L. Trache, "ChETEC follow-up in Horizon 2020 and Horizon Europe Programmes", workshop in Dresden on November 11-12, 2019. Presentation. Supported by ChETEC.

ChETEC is the COST Action CA16117 "Chemical Elements as Tracers of the Evolution of Cosmos".

## 5. List of Appendices

Appendix 1: papers

#13. L. Trache and F. Carstoiu, "*Indirect methods in Nuclear Astrophysics*", http://arxiv.org/abs/1911.06077

#7 A.I. Chilug et al. NN2018, , in *Proc. Nucleus-Nucleus Collisions 2018, Saitama, Dec. 2018*, **Jap Phys Soc Conf Ser**, accepted July 2019.

*Nuclear Breakup and Coulomb Dissociation of 9C Nucleus Studied at RIBF RIKEN*

#1. Alexandra Spiridon, Emmanuel Pollacco, Antti Saastamoinen, Robert E. Tribble, George Pascovici, Livius Trache, Bertrand Mehl, Rui de Oliveira, **Nuclear Inst. and Methods in Physics Research, A 943** (2019) 162461

*A study in using MICROMEGAS to improve particle identification with the TAMU-MDM focal plane detector*

Appendix 2: Indicatori de realizare intermediara

Consider ca obiectivele fazei au fost pe deplin indeplinite.

Director de proiect,
Dr. Livius Trache

Livius Trache IFIN

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Magurele, Nov. 15, 2019

# Indirect Methods in Nuclear Astrophysics

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Abstract

This paper follows the inaugural talk one of the authors (LT) gave at the opening of the ECT* workshop with the same title, which he co-organized in Trento, Italy, November 5-9, 2018. As such it follows the ideas expressed there, which were to outline the discussions that the organizers intended for that meeting. Therefore, the paper will review the indirect methods in nuclear astrophysics, their use and their specific problems, old and new, the need to further developments rather than giving complete treatments of each method or reviewing exhaustively the existing literature. The workshop was from its inception aiming also at reviewing the status of the field of nuclear astrophysics and its connections with adjacent branches of physics. Some lines on these are included here.

**Keywords: Nuclear astrophysics, nuclear physics for astrophysics, indirect methods, Coulomb dissociation, one-nucleon transfer, nuclear breakup, resonances, Trojan Horse method, decay spectroscopy**

**PACS numbers:** 26.50.+x; 25.60.-t; 25.60.Je; 25.60.Gc

**Citation:** L. Trache, F. Carstoiu, *Indirect Methods in Nuclear Astrophysics*, Sci. China-Phys. Mech. Astron. , 000000 (2019), doi: 10.1007/s11433-000-0000-0

## 1 Introduction

As announced in the abstract, this paper follows the introductory remarks given at the ECT* workshop "Indirect Methods in Nuclear Astrophysics" (IMNA), Trento, Italy, November 5-9, 2018 [1]. The remarks announced the main topics, how the organizers setup the invited speakers list and the way they conceived the progress of the lectures and of the discussions.

We start from the premise that nuclear astrophysics (NA) is in the last few decades an important part of the science programs of all nuclear physics laboratories. Moreover, especially in a time when the concept of multi-messenger observations becomes not only used and validated by the scientific community, but widely known to the larger public, nuclear astrophysics must be redefined to include (or being close to):

- Nuclear physics for astrophysics (NPA)

- Stellar dynamics
- Nucleosynthesis modelling
- (specific) astrophysics observations: X-ray and Gamma-ray space telescopes, cosmochemistry.

Even Cosmology – a very large field in itself - becomes closer to NA and there are mutual benefits.

These said, there is clearly a need for closer interaction among the specialists in these fields. It is obvious from the title of the workshop that the focus was intended to be nuclear physics for astrophysics, but we appealed to specialists in the adjacent sub-fields listed above to come and talk about the progress on specific topics of interest and in particular about their needs for new or more precise nuclear data. Similarly, we wanted them to listen to talks about the current possibilities, limitations and problems of the nuclear physicists working with indirect methods for nuclear astrophysics.

As such the main topics in Nuclear Physics for Astrophysics, related to indirect methods to be discussed were:

- Nuclear astrophysics for practitioners, basics. Nuclear data needs;
- Stellar dynamics, nucleosynthesis modeling, observations;
- Review of existing indirect methods in nuclear astrophysics:
    - “the list”;
    - Specifics. Assessment of problems with the accuracy of each indirect methods, experimental and theoretical, the importance of calculated absolute values;
    - The need for modern theories and codes; parameters to use in calculations;
- Review of experimental methods, equipment and specifics;
- New facilities, including RIB facilities, and their nuclear astrophysics programs;
- Related topics – new directions.

While as announced, the paper is based on the inaugural ECT* talk, in a few cases we will add figures to illustrate better the indirect methods described. In most of the cases we will use illustrations from own work, for reasons easy to understand, some already published or shown at past conferences. We felt this need for illustrations because presumably the readership for this paper is wider and less knowledgeable in this topic than the workshop’s attendees. We will insist more on giving general descriptions of the basic ideas of the methods, their potential and of the needs for improvements, rather than exhaustive discussions and examples. Will send the interested reader to suitable literature.

The paper is structured as follows: after this Introduction, in Sect. 2 a few general considerations on NPA methods are given to set up the framework and substantiate the later discussions. In Sect. 3 after a short discussion on the paradigm used in IMNA, a list of indirect methods is given, while each method is briefly discussed in the subsections of Sect. 4. Section 5 closes with discussions on a few adjacent topics of nuclear astrophysics and some conclusions.

## 2. Nuclear physics for astrophysics

We know for about a century that nuclear reactions are the fuel of the stars (Edington, 1920) and the origin of chemical elements in the Universe. This latter through phenomena called globally nucleosynthesis that took place both in the Big Bang [2] and later in stars (see Burbidge, Burbidge, Hoyle & Fowler [3] and Cameron [4], both 1957). We also know that it continues today (see, e.g. [5] or think about the Sun [6]). There is no doubt about these in the scientific community, which means that there are proofs or many arguments for these statements! All these proofs are based on astrophysics observations and on quantitative modelling of nucleosynthesis, using nuclear data. However, we are far from understanding fully nucleosynthesis, to know the places where various processes have happened, or from having a good quantitative description for them, etc. These are subjects that nuclear astrophysics deals with.

We will not treat here the basics of nuclear astrophysics, will not introduce concepts like the astrophysical S-factors, reaction rates, Gamow window and will rather refer the reader to many introductory texts, like [7], e.g., if necessary.

Nuclear Physics for Astrophysics in particular, aims at providing data and models for the understanding of the origin of chemical elements in the Universe. We do not have a complete quantitative explanation of the creation of all elements, despite many successes in the last decades.

There are two types of experiments in nuclear physics for astrophysics:

- *Direct measurements*, that is to reproduce and measure in the nuclear physics laboratory the reactions that happened or happen in stars, at exactly those relevant energies (in the Gamow window). The latter is a big problem, as the "stars are cold" on nuclear physics' scale of energies, and for reactions between charged particles the Coulomb barrier leads to very small cross sections and these experiments are difficult. At low energies the signal-to-background ratio becomes very small and special measures must be taken to improve it. In most cases the data had to be extrapolated down to energies in the Gamow window. Progress was made and will continue using underground laboratories, existing (LUNA at Grand Sasso National Laboratory) or planned (in USA, China, etc.). It is not that far back in time that the first measurements in the Gamow window were made [8], avoiding uncertain extrapolations.
- *Indirect measurements:* experiments are done using beams at nuclear laboratory energies of 1s, 10s, 100s MeV/nucleon to extract data to be used for the evaluation of cross sections at energies of 1s, 10s, 100s of keV/nucleon, relevant in stars. There are two main reasons we must resort to indirect methods in NA:
  - The very low cross sections mentioned above when we attempt reactions at energies relevant in stars (1s-100s keV).
  - Many, in fact most, of the reactions occurring in different NS processes involve unstable nuclei. Therefore, we need to use radioactive species for the experimental determination of needed nuclear data. Only a few experiments could be done with radioactive targets for situations where the nuclides involved have a reasonably long lifetime and can be produced ($^{7}$Be [9], $^{22}$Na [10], to mention only the pioneering ones), but mostly we use radioactive ion beams (RIB). Moreover, as the direct measurements are very difficult even with stable nuclei, as said before, due to the very low cross sections, measurements at low energies with unstable species are out of experimentalists' reach for now (there are pioneering attempts with decelerated beams at GSI [11], though, and soon at other places). Therefore, most of the reactions involving unstable nuclei are being studied using *indirect methods*. We shall review these methods here.

There are tens of thousands of nuclear reactions and nuclear processes that occur in stars. Some are very important, some are less important, and some may be irrelevant in one type of process, while becoming important in another, depending on the conditions of the particular process and environment: composition, densities and temperatures involved. There are also many nucleosynthesis processes, and our knowledge about them differs. To have an evaluation of which data are of importance and in which circumstances, to what precision they are necessary for good, reliable, nucleosynthesis modelling, is very important for those of us working in obtaining data for nuclear astrophysics. It is a crucial point and on its importance we insisted at the workshop but will not discuss here.

## 3. Indirect Methods in Nuclear Astrophysics. The list.

Before going to make the list of the indirect methods for nuclear astrophysics, we have to say that it has to be, by necessity, a personal view of the current list. The methods can be organized and certainly ordered differently than below. We would start by saying that the first indirect nuclear data that were used for astrophysics were the mass measurements of the early XX-th century. Those measurements and the $E=mc^2$ of A. Einstein lead Sir A. Edington to suppose that solar energy arises from nuclear reactions. Further, the beta-decay studies allowed Critchfield and Bethe to propose and evaluate the pp-chain of reactions [12]. Then the lack of knowledge on the mass gaps at A=5 and A=8 lead to the wrong, but historically important, model of nucleosynthesis by Alpher, Bethe and Gamow published on April 1, 1948 [13]. And one could go on and on!

However, explicit proposals for indirect methods in nuclear astrophysics started gaining momentum in the mid-eighties of last century.

The list of IMNA, as presented and discussed at the workshop is:

A. Coulomb Dissociation
B. Single-nucleon transfer reactions – the ANC method
C. Nuclear breakup reactions
D. The Trojan Horse Method
E. Spectroscopy of resonances, a wide category of reactions, types of experiments and theories.

While it is clear that the indirect methods in the list above may differ from one another by laboratory energies at which they are applied and by the techniques used, both experimental and theoretical, there is a common path from their results to the evaluation of the cross sections or reaction rates at energies or temperatures relevant in stellar processes:

1. Experiments are made at energies usual for the nuclear physics laboratories
2. Theoretical (reaction) calculations are made
3. The experimental results of step (1) are compared with calculations of step (2) to extract nuclear information (typically nuclear structure parameters)
4. The extracted information is used to evaluate nuclear astrophysics data: cross sections, astrophysical S-factors or reaction rates.

These steps are also sketched in Figure 1. There (B on the right-hand side) a point is also made to show that in both steps 2 and 4, additional knowledge is very important. The theories and the parame-

ters used in both situations, at large and at low energies, need to be well established and vetted throughout in order to give confidence on the end results. We should stress that most of the time it is important to have good, reliable calculations of the absolute values at point (2), a feature not exactly common to nuclear reaction theories. Another point that is not figured there and not specified above is the importance of the choice of the data/information that we extract at point (3), their relevance for the precision of the evaluation at step (4), and in particular the need that they are model independent, as much as possible. This will be exemplified when the ANC method Bill be discussed.
Another important step is to compare the results of the indirect methods (step 4) with results of direct measurements, if they exist (A, on the left side of the figure).

We shall start discussing them briefly in list's order.

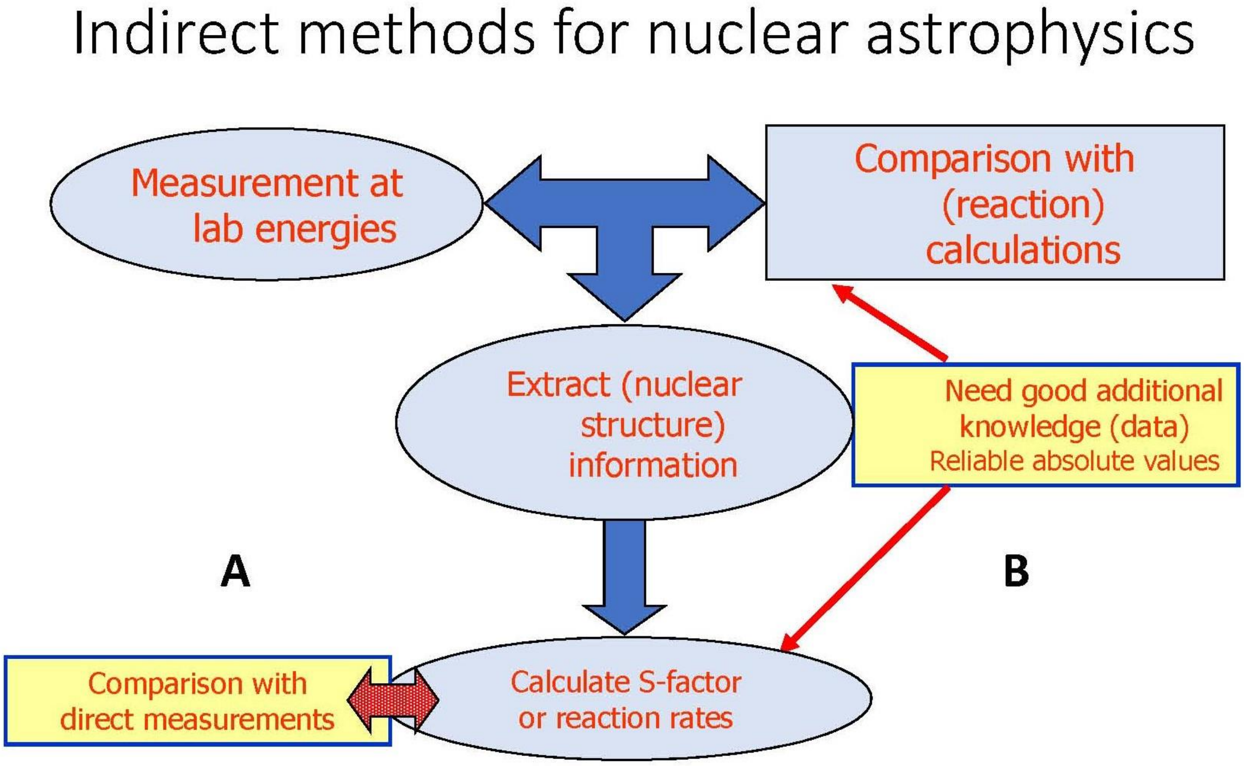



**Figure 1. The paradigm used in Indirect Methods in Nuclear Astrophysics.**

## *4. Indirect Methods in Nuclear Astrophysics*

### *A. The Coulomb dissociation*

The Coulomb dissociation is a method specifically introduced for nuclear astrophysics over thirty years ago. Schematically, it works as follows.

- Instead of studying the **radiative proton capture reaction** X(p,$\gamma$)Y at a definite center-of-mass energy $E_p$, a process in which a gamma-ray of energy $E_\gamma = E_p + S_p$ is emitted ($S_p$=binding energy of the proton in nucleus Y) after the capture of a proton, we could measure the inverse process: **photodissociation**. A photon of energy $E_\gamma$ produces the dissociation Y + $\gamma$ → X +p, in which a proton-core system of relative energy $E_p = E_\gamma - S_p$ results. Then the Fermi golden rule of detailed balance can be used to relate the cross section of the two processes. Obviously, the energy of the photon involved must be larger than the binding energy $S_p$.
- Baur, Bertulani and Rebel [14] proposed **to replace the real photons** needed in **photodissociation with virtual photons**. A fast-moving projectile Y in the Coulomb field of a target senses a field of virtual photons that induces the dissociation of the projectile Y → X + p. The resulting cross section for Coulomb dissociation is a product between the photodissociation cross section and the number of virtual photons of each multipolarity and energy needed:

$$\boxed{\frac{d^2\sigma}{dE_\gamma d\Omega}(E_\gamma,\theta) = \frac{1}{E_\gamma}\left[\frac{dN(E1,E_\gamma)}{d\Omega}\sigma_{E1}^{photo}(E_\gamma) + \frac{dN(E2,E_\gamma)}{d\Omega}\sigma_{E2}^{photo}(E_\gamma) + \ldots\right]}$$

To increase the effect, a strong Coulomb field of a high Z target is needed (Pb for example). Only the photons with energies higher than $S_p$ contribute in the dissociation and a continuum spectrum of relative energies $E_p$ is obtained. The photodissociation cross section is then directly related to the radiative capture cross section sought in nuclear astrophysics.

Problems arise from:

- the need of relatively large projectile incident energies to produce enough virtual protons of the large energy $E_\gamma > S_p$ necessary to produce photodissociation. This condition is easily satisfied by the new RIB facilities.
- the fact that different multipoles do contribute in different proportions in Coulomb dissociation and in radiative capture (see eq. above). Therefore, the disentangling of different multipole contributions from angular distribution measurements in Coulomb dissociation is needed before transforming the results into astrophysical S-factors for radiative capture. That is experimentally very demanding at the large projectile energies necessary to satisfy the first condition. Mostly one relies on calculations so far, but setups are conceived currently to resolve this experimentally [15].
- the difficulty to separate the contribution of the nuclear and Coulomb fields in dissociation at large energies. This is done selecting dissociations that happen at large impact parameters, which translates into measurements very close to zero degrees, experimentally a very difficult task. The

problem is further complicated by the (usually) poor definition of the currently available radioactive beams.

However, a large number of very good Coulomb experiments have been done so far to obtain astrophysical data, and the method is considered rather well established [16]. One important conceptual advantage of the method is that from Coulomb dissociation the energy dependence of the astrophysical S-factor $S(E_p)$ can be experimentally extracted ($E_p$ = p-core relative energy). While experimental difficulties restrict measurements very close to the threshold, that is at the equivalent of capture energies in the Gamow window, and therefore one needs again extrapolations, the measurement of the excitation function S(E) may also give information about the location and widths of low energy resonances of potential importance in nuclear astrophysics.

Currently the method is considered appropriate for use with proton rich radioactive beams at intermediate energies obtained through projectile fragmentation. However, there are no principle restrictions to use it for radiative alpha capture reactions (attempts were made and further ones are planned to study the Coulomb dissociation of $^{16}O\rightarrow \alpha+^{12}C$, the inverse of the $^{12}C(\alpha,\gamma)^{16}O$ reaction).

The method needs further improvements in experiments, in particular in the multipole decomposition, while in theory further attention must be given to the interference with the nuclear component. It is clear that Coulomb dissociation will remain an important tool for nuclear astrophysics in the era of radioactive ion beams.

## *B. Single-nucleon transfer reactions – the ANC method*

A direct reaction is characterized by the involvement of a limited number of degrees of freedom, or the rearrangement of one or of a few nucleons during a fast process. From the early days of nuclear physics, nucleon transfer reactions were the way to study the single-particle degrees of freedom of nuclei. Typically, spectra of final states and angular distributions are measured. Due to the direct character of the interaction, the tool of choice for the description of transfer reactions is the Born Approximation, either in the Plane Wave (PWBA), or the Distorted Wave (DWBA) form:

- by comparing the shape of the measured angular distributions with DWBA calculations, the quantum numbers *nlj* of the single-particle orbitals involved could be determined (not always uniquely), and
- by comparing the absolute values of experimental cross sections with those calculated, the spectroscopic factors $S_{nlj}$ can be determined for the states populated.

The spectroscopic factor is proportional to the "probability" that a many-body system (the nucleus) is found in a certain configuration. In the case we are talking about, transfer of one nucleon to/from a single particle orbital with quantum numbers *nlj,* the classical definition (from Macfarlane and French, 1960 to Bohr and Mottelson, 1969) relates the spectroscopic factors *S(nlj)* to the occupation number for the *nlj* orbital in question. One nuclear state may present several spectroscopic factors due to configuration mixing: e.g. the ground state (g.s.) of $^8B$ has $S(p_{3/2})$ and $S(p_{1/2})$, related to the probability that the last proton is bound around the g.s. of the $^7$Be core in a $1p_{3/2}$ and a $1p_{1/2}$ orbital. The determination of spectroscopic factors from one-nucleon transfer reactions was and is crucial in building our current understanding of the fermionic degrees of freedom in nuclei and their coupling to other types of excitations. However, in determining the absolute values of the spectroscopic factors as the ratio between the experimental cross section and the DWBA calculated cross section one makes (1) a strong assumption that the single-particle configuration assumed is dominant in the wave function (actually in the contribution to the cross section measured) of the state under consideration and (2) that the parameters used in the DWBA calculations are appropriate.

A connection between transfer reactions and nuclear astrophysics was made in the 1970s by Claus Rolfs [17] but in the opposite direction (NA gives info about nuclear spectroscopy). The Asymptotic Normalization Coefficient (ANC) method is an indirect NA method introduced systematically by the Texas A&M group and successfully and extensively used to determine astrophysical S-factors for the non-resonant component of radiative proton capture at low energies (zero to tens or hundreds of keV) from one-proton transfer reactions involving complex nuclei at laboratory energies (about 10 MeV/u) [18-20]. The method was explained in detail in many previous publications, we summarize the main ideas below and in Figure 2, taken from Ref. 21. Essentially it works around the problem of the considerable dependence of the absolute values of the extracted spectroscopic factors on the parameters used in the DWBA calculations. It works for cases where the transfer reactions are peripheral, a condition that may be fulfilled by choosing the target-projectile combinations and the bombarding energies. We shall go briefly through the basics of the method.

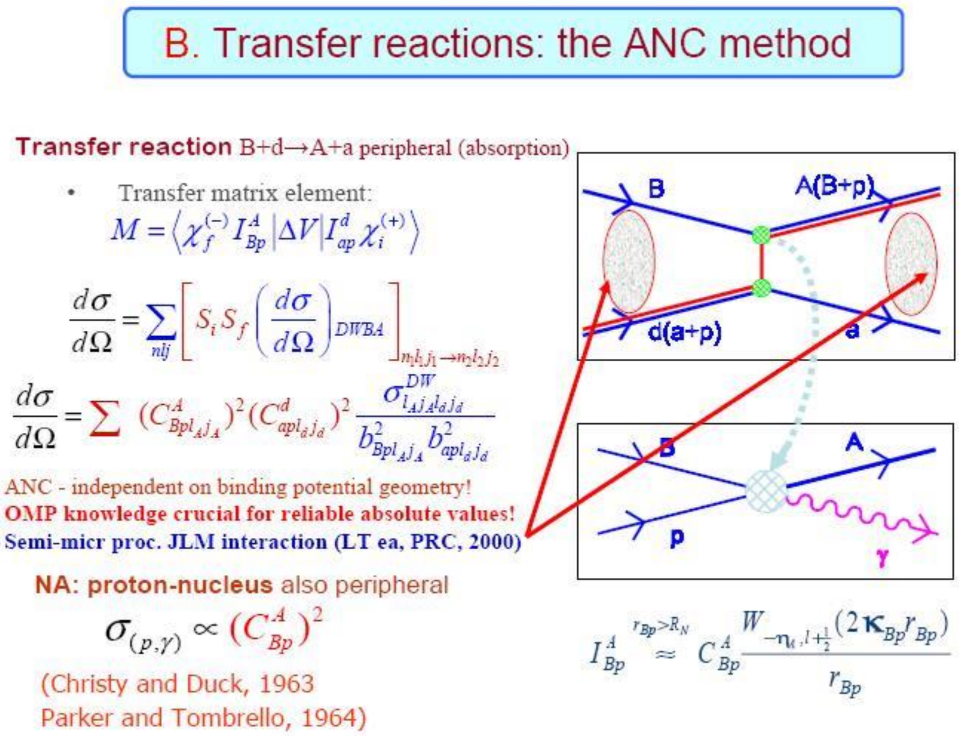



**Figure 2. The Asymptotic Normalization Coefficient method compactly explained (see text).**

We use peripheral proton transfer reactions to extract the ANCs, which can be used to evaluate (p,γ) cross sections important in different types of H-burning processes. The idea behind it is that in peripheral processes it is sufficient to know the radial wave functions at large distances, and this asymptotic radial behavior is given by a known Whittaker function times a normalization coefficient $C_{nlj}$ (this is the asymptotic normalization constant, or ANC, as in the equation on the lower right corner of Fig. 2). That allows the evaluation of the overlap integrals ***I*** which enter in the DWBA calculations (first equation in Figure 2) and from there $C_{nlj}$ can be determined by comparison with the experiment. In the transfer reaction B(d,a)A one has to know one of the two vertices (the spectroscopic factor $S_i$ or the ANC for one vertex, the lower in the top diagram on right) to determine the spectroscopic factor $S_f$ or the ANC for the other one. And from there one can calculate the radiative capture cross section for the B(p,γ)A process (lower diagram on right) as it is only sensitive to the peripheral behavior of the overlap integral. The quantities $b_{nlj}$ are the single-particle ANC, that is, the asymptotic coefficients for the radial functions normalized to unity. These are those used in the DWBA calculations. It has been shown that extracting the ANC is less parameter dependent than extracting spectroscopic factors (see Fig. 11 in [18], e.g.). The parameters varied here are those defining the geometry of the Woods-Saxon well that binds the proton around the core: the reduced radius $r_0$ and the diffuseness $a$. Figure 2 also stresses the importance of having good and reliable optical model potentials (OMP) to make the DWBA calculations, a problem we will discuss later here. Note: the independence of the ANC extracted from the parameters of the Woods-Saxon potentials used to calculate the radial wave functions above should not be confused with an independence on the parameters of the typically Woods-Saxon shaped optical model potentials used to calculate the distorted wave functions of the scattering! Good care should be taken to extract or evaluate good OMP in both the entrance and exit channels of the reaction. The absolute values depend very much on these OMP parameters, in most cases more than on the $(r_0,a)$ parameters of the proton-binding potential well.

The ANC method was used in several experiments of this type. We will show a typical one of the studies, on the $^{12}$N(p,γ)$^{13}$O proton capture reaction at stellar energies. It uses the proton transfer reaction $^{14}$N($^{12}$N,$^{13}$O)$^{13}$C with a $^{12}$N beam at 12 MeV/u [22]. Figure 3 below, also the image of a slide shown during a lecture on the subject, summarizes the whole process, from extracting the data from experiment to nuclear astrophysics conclusions. Going from bottom left, clockwise:

- we have measured the elastic scattering and the one-proton transfer using a $^{12}$N beam produced and separated with the MARS spectrometer [23] at Texas A&M University. The elastic scattering data (lower left corner) were used to determine the OMP needed in the DWBA calculations for transfer.
- The ANC for the system $^{13}$O→$^{12}$N+p was extracted from the transfer data (top left) after which
- the ANC was used to evaluate the non-resonant component of the astrophysical S-factor for the radiative proton capture $^{12}$N(p,γ)$^{13}$O and the corresponding reaction rate as a function of stellar temperature (top right).
- Finally, the astrophysical consequences are shown in a plot (bottom right) which shows the region of density-temperature where the capture process competes with its competitor (β-decay), in first stars (above the full line 1). For comparison, the curves from literature before our data were

measured are shown. There is a big change from the original estimates (dashed curves) based on theoretical estimates only, showing the importance of experimental measurements.

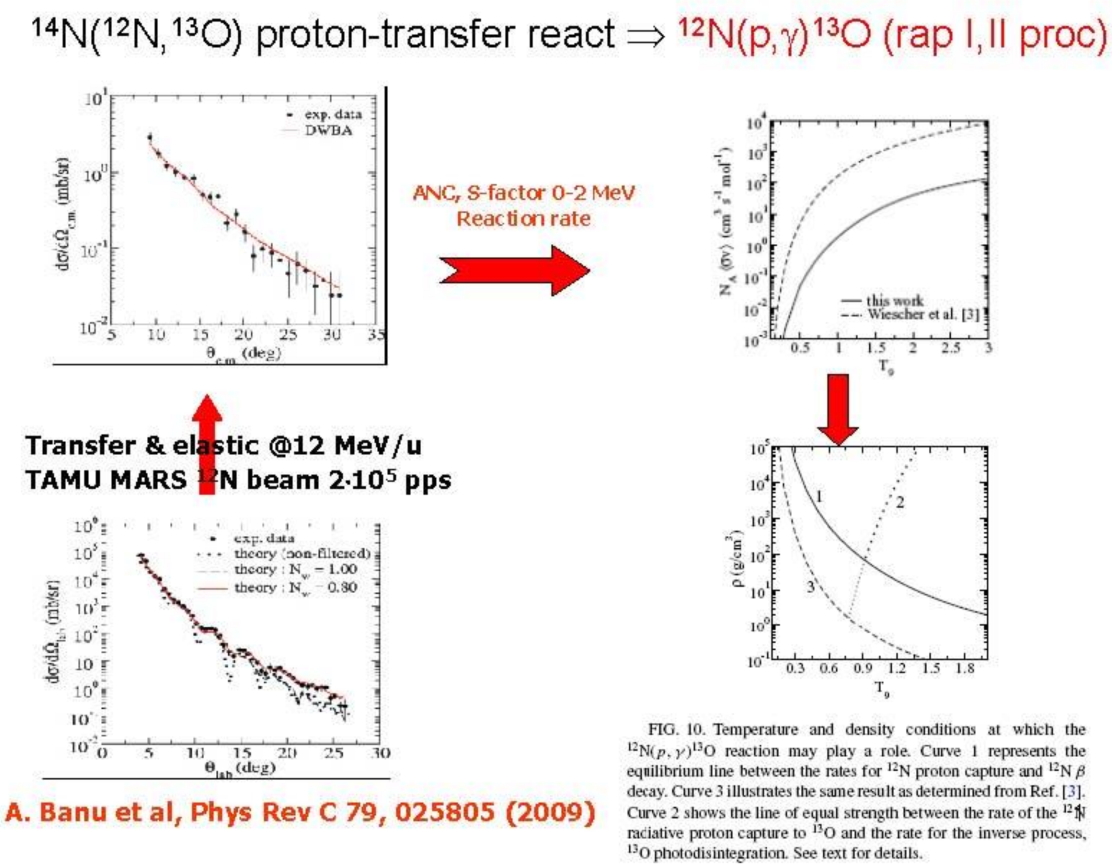



**Figure 3. Summary of how elastic and one-proton transfer data measured with secondary RIB (clockwise from lower left side along the arrows) are transformed in nuclear astrophysics information (bottom right side) (from Ref. 21).**

A variation of the ANC method uses one-neutron transfer reactions to obtain information about the mirror nuclei, for example studying the $^{13}$C($^{7}$Li,$^{8}$Li)$^{12}$C reaction to determine the ANC for $^{8}$Li which one then translates into the corresponding structure information (the proton ANC) for its mirror $^{8}$B and from there $S_{17}(0)$ for the reaction important in the neutrino production in Sun $^{7}$Be(p,γ)$^{8}$B [6]. We did this using the mirror symmetry of these nuclei: the similarity of their wave functions, expressed best by the identity of the neutron and proton spectroscopic factors for the same *nlj* orbital in the two nuclei $S_p(nlj)=S_n(nlj)$ (of course, the radial wave functions are not identical!). The experiment using these concepts and the results were published in Ref. 24.

We mentioned before that in order to extract data, either the spectroscopic factors, or the ANCs, the experiments must be compared with calculations, and in the above conditions, the knowledge of the optical potentials is crucial. This is an important problem, with no clear solution so far and on which we need better data and better theories and codes. There is not only the usual problem that we know from elastic scattering data that the OMP extracted for nucleus-nucleus interactions are not unique, but the current quality of elastic scattering data with radioactive beams is not sufficient to extract good OMP. In order to avoid the ambiguities usually related to the fits of the elastic scattering data, better data are needed, especially data extended to larger angular ranges, including data at backward angles, where the cross sections become very small. There are several attempts to establish procedures leading to reliable predictions for optical potentials, none globally accepted. Certainly, more work is needed in this direction: experiments, systematics and theoretical analyses. We want to draw the attention here that we do not only need 'new data' for this purpose, but 'better data' as well, in order to advance on this topic, of crucial importance in many types of experiments involving radioactive beams. The matter was discussed at the workshop, but the only conclusion was "more work is needed, better data are needed". This may imply better and more precise data possible only with stable beams. A proposed line of work is that of our group that has established a procedure based on double folding, starting from an effective nucleon-nucleon interaction called JLM and many successes were obtained with it. We will not insist on this here, but we send you to literature [25].

We conclude that while the experimental conditions when using transfer reactions with RIBs need improvement, resolutions in particular, angular and energy resolutions, further work is due also in theory. Not only the improvement on OMP, but on reaction theories, codes and parameters. Careful evaluation of the improvements brought in by the increased use of extended calculations, like the use of coupled channels discrete calculations (CCDC) must be discussed and assessed.

## C. Nuclear breakup reactions

After the discovery of the first halo nucleus $^{11}$Li [26], much work was done for the study of radioactive beams, and in particular of loosely bound nuclei. Several laboratories have demonstrated that one-nucleon removal reactions (or breakup reactions) can be a good and reliable spectroscopic tool for such nuclei. In a typical experiment a loosely bound projectile at energies above the Fermi energy impinges on a target and loses one nucleon. The momentum distributions (parallel and/or transversal) of the remaining core measured after reaction were relatively easy to measure and they gave information about the momentum distribution of the removed nucleon in the wave function of the ground state of the projectile. The shape of the distributions was shown to be sensitive to the quantum numbers *nlj* of the single particle wave function (determining unambiguously only the orbital angular momentum *l*; shell model systematics are needed for the others) and in some cases even to assess the mixing of different configurations in the ground state wave function of the projectile (see Sauvan [27] for example). At later stages coincidences between the cores and gamma-rays allowed even for the determination of complex configuration mixings. Most of the cases studied involved neutron removal reactions on light targets like Be or C, where the nuclear breakup dominates. The method is also valuable because it can be applied using low quality radioactive ion beams available so far: low intensities, down to a few pps, and poor definition (energy and direction resolutions). Typically, these beams were/are from fragmentation reactions and the energies for which the technique is applicable must be above the Fermi energy in nuclei, intermediate energies E>25-50 AMeV (which is always the case for fragmentation).

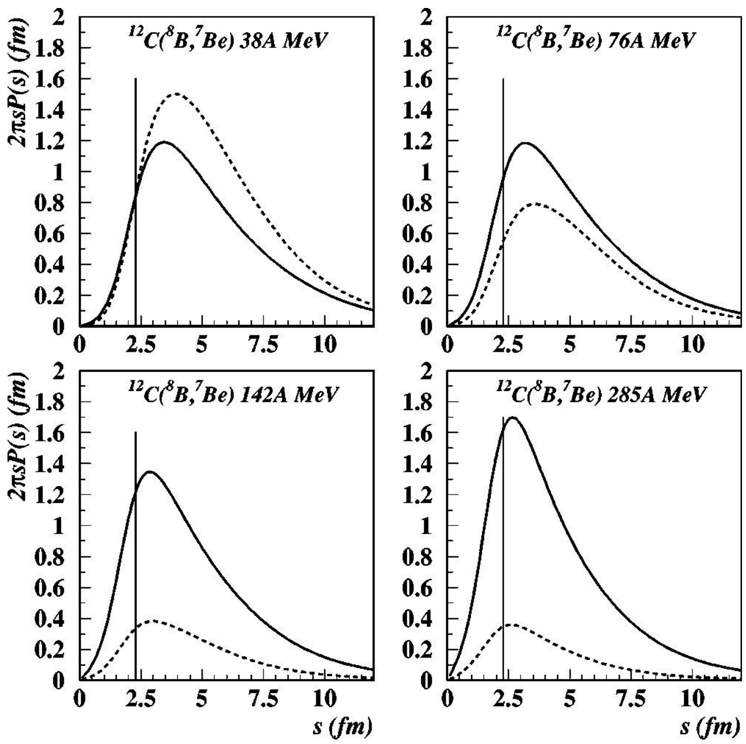



**Figure 4. The breakup probability profile as a function of the impact parameter for the case of $^{8}$B→$^{7}$Be+p on a light target at various energies. The vertical line shows the position of the $^{7}$Be core rms radius. The stripping (full lines) and diffraction dissociation (dashed lines) components are shown. From Ref. 29.**

Later it was shown in Ref. 28 that on a large range of projectile energies breakup reactions are peripheral (Figure 3) and, therefore, the breakup cross sections can be used to extract asymptotic normalization coefficients. In cases where one proton removal $Y \rightarrow X + p$ is studied, the ANC found can be used to evaluate the corresponding radiative proton capture cross sections $X(p,\gamma)Y$ at very low energies, useful in NA. For these to be correct, on one hand one must measure the absolute values of the breakup cross sections and to have reliable reaction model calculations and tested codes and parameters, on the other hand. The calculations must reproduce the available data from measurements in order to be tested. This is a very important point, which we stressed in the workshop. The method to use breakup reaction for nuclear astrophysics was first applied in [28, 29] to the breakup of $^{8}B$ to determine $S_{17}(0)$. It was shown that all available breakup data, on targets from C to Pb and at energies from 27 MeV/u to 1400 MeV/u lead to a consistent value for the ANC for $^{8}B \rightarrow {}^{7}Be+p$. Different reaction models and different nucleon-nucleon effective interactions were used. The overall uncertainty estimated at about 10%, which is a very good agreement, a fact that validated both the $S_{17}(0)$ adopted in the neutrino production calculations pertinent to what was called the “solar neutrino puzzle” before the neutrino oscillations were demonstrated, and the validity of this indirect method in NA.

One other example useful to mention here is the breakup of $^{23}Al$ at intermediate energies. It is a more complex experimental situation where several configurations contribute to make the ground state of the $^{23}Al$ projectile. The ground state of this projectile has configuration mixing (it turned out to be 4 different configurations). The participating configurations were disentangled using the coincidences between the $^{22}Mg$ core and the resulting gamma-rays. In the end the ANC for the $^{22}Mg(0+)$*proton configuration (the only one entering the inverse radiative proton capture reaction $^{22}Mg(p,\gamma)^{23}Al$) was extracted and used to evaluate the continuum contribution to the reaction rate. However, pertinent reaction rate (the NA result) was only obtained combining the result of this nuclear breakup experiment with that of the Coulomb breakup of the same projectile needed to evaluate the contribution of the resonant part. It is treated in the paper by A. Banu *et al*. and we refer the reader to it [30].

The uncertainty of 10-15% estimated for this method arose from a combination of experimental uncertainties but also from those of the calculations, using various approaches and effective nucleon-nucleon interactions. Question here are if this is 1) sufficient for NA and 2) if we have sufficient confidence in the types of calculations and parameters used? The answer to the first question is probably “yes, in most cases”, while the second needs further work (this is the opinion of an experimentalist!). Which would mean that further work is needed to certify the reaction mechanism(s) of breakup – are those assumed the real ones? – and of the theoretical approaches used. To answer to the first question, we may need to use exclusive measurements, rather than inclusive ones, a task possible at the new RIB facilities.

## *D. The Trojan Horse Method*

This method is one of the most subtle among the indirect methods and is fully dedicated to nuclear astrophysics applications. It could also be called “the most direct of indirect methods in nuclear astrophysics”. While it was initially proposed at about the same time as Coulomb dissociation by G. Baur [31], it was actually re-formulated and applied first at the end of the nineties (of the XX c.) by the Catania group lead by prof. C. Spitaleri. Many applications were made since by the same group of initiators, with experiments in Catania or in other laboratories. See e.g. [32-35], to just give a few examples. Theoretical developments were made in parallel, see [36, 37] and [20].

Briefly, the method works as follows. Instead of attempting the $A+x \rightarrow c+ C$ reaction at very low energies, experiment made difficult by the Coulomb barrier between charged nuclei $A$ and $x$, one does the experiment with 3-bodies in the final channel $A+a \rightarrow c+C + s$, at higher energies, above the Coulomb barrier. The projectile $a$ is chosen to be have a good cluster configuration $a=x+s$ in its ground state and the kinematic conditions are chosen such that the nucleus $x$ is moving slowly relative to the target $A$. This can stem from a combination of the projectile energy and the relative internal energy of $x$ and $s$ inside the compound $a$. While the relative energy $A$-$x$ is as low as in stellar reactions, $x$ is already beyond the Coulomb barrier and the reaction of interest takes place with larger probabilities. In the same time the nucleus (or nucleon) $s$ is a spectator. These are called quasi-free mechanism conditions. They must be fulfilled for the method to be applicable. With these kinematic conditions fulfilled, that is with the quasi-free mechanism present in reaction and with the cluster configuration of the projectile $a$ proven, one can make a direct connection between the triple differential cross section of the 3-body reaction measured and the cross section of the 2-body reaction at very low energies. The connection is easier to prove in the plane wave impulse approximation but is valid also in the distorted wave approximation. We send the reader to the detailed discussions in [20, 36, 37] and references therein.

To summarize, there are two main achievements of the THM:

- One can obtain data for very low energies, otherwise not accessible. In particular the behavior of the excitation functions close to $E_{cm}=0$ (or even below, see Ref. 34 for that). One can obtain the position of very low resonances and their widths and/or the contribution of sub-barrier resonances in cases where other methods fail [34].
- As the reaction A+x happens inside the barrier, it is a reaction between naked nuclei, with no screening from the electrons of the target and projectile, as is usually the case in direct laboratory measurements. There is no screening in stellar plasmas. Comparing the results of THM measurements with those of very low energy direct measurements one can obtain valuable and unique information about screening in nuclear reactions.

The method is useful in determining the behavior of the cross sections at very low energies but so far relies on normalizing the absolute values predicted to existing data at larger energies from direct measurements. The proportionality factor predicted by theory is not yet calculated. There are also discussions about the validity of the simpler plane wave approximation. Codes have been worked out to fit the data with multiple, overlapping resonances, they need to be further tested before being accepted by all parts in the discussions.

Recently the method could be applied for the first time for radioactive beams [35].

### E. Spectroscopy of resonances

Besides the continuum parts contributing to the reaction rate in stellar processes, contributions may occur from resonances. These resonances are meta-stable states in the compound nuclear system produced in reaction as an intermediate step in a two-steps process. The contribution of an isolated resonance at energy $E_r$ to the reaction rate of a stellar process at temperature T is given by [7]:

$$\langle \sigma \upsilon \rangle_{res} = \left( \frac{2\pi}{\mu kT} \right)^{3/2} \mathrm{h}^2 \omega\gamma \exp\left( -\frac{E_r}{kT} \right)$$

To evaluate the corresponding contributions to the reaction rates it is therefore, enough to determine the location of the resonances ($E_r$) and their resonance strengths ($\omega\gamma$) [7].

$\omega\gamma = (2J+1)/[(2j_i+1)(2j_o+1)]\ \Gamma_{in}\Gamma_{out}/\Gamma_{tot}$

The important resonances are located at very low energies, in the Gamow window, or around those energies (see for example [38]).

These quantities (actually the resonance strength is more than one parameter: we need the spin J of the state and the partial widths $\Gamma_{in}$ and $\Gamma_{out}$, with $\Gamma_{tot}=\Gamma_{in} + \Gamma_{out}$)) may be determined by studying the spectroscopic properties of the corresponding meta-stable state, populated through another, more convenient method than the low energy direct measurement (we use standard and obvious notations here). Both are equally important, as the dependence on the position of the resonance is exponential, and the resonance strength intervenes multiplicatively. In all cases the information on the quantum numbers (spin and parity $J^\pi$) for states located in the sensitive region is very important, because it tells if the meta-stable states in question can indeed be resonances that can contribute in the reaction studied. This is because at the low energies in stars only low partial waves (*s* or *p*) can typically contribute.

The types of measurements usable is obviously very large and diverse, and the list below is only schematic:

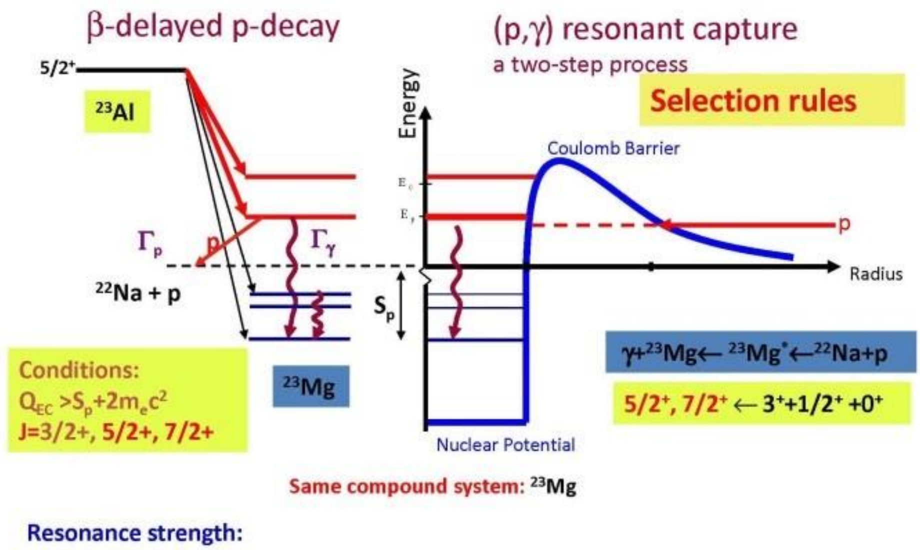
1. Transfer reactions
2. Gamma-ray spectroscopy
3. Beta-delayed proton emission
4. TTIK - Thick Target Inverse Kinematics scattering
5. Other spectroscopic methods.

It is beyond the scope and possibilities of this article to discuss each of them or give an exhaustive list of references. We would need to review virtually all nuclear physics spectroscopic methods to do that. Instead we only outline that all cases in experiments we attempt:

- To find the meta-stable states that may be resonances and determine their energy $E_r$
- To determine the spin and parity of the state, establish if the state found can be a contributing resonance in the reaction in stars
- Measure the partial widths that can lead to the determination of the resonance strength.

Without detailing further, we will just say that any experienced nuclear physicist knows that the latter is the most demanding of the steps!

*Decay spectroscopy.* We shall sketch only one of the types in the list above, *beta-delayed proton emission (βp)*, as it is newer, closer to us, and is becoming more frequently used due to the progress in the production of exotic nuclei in the new RIB facilities. This will also allow us to stress the improvements required in the experimental setups to obtain NA valuable information. The method works like this: instead of measuring radiative proton capture (p,γ) one can study the inverse of its first step, the proton decay of the same state. The decaying states are populated by beta-decay: in the same compound nucleus, states above the proton threshold are populated by β-decay, and then they decay emitting a proton. The method is applicable if the selection rules for (p,γ) and βp allow for the population of the same states (by the energy and spin-parity selection rules). One can determine that way the energy of the resonance, determine or restrict the spins and parity of the states involved and determine the branching ratios. This simple connection is schematically presented in figure 4 below From Ref. 21) for the case of the $^{22}$Na(p,γ)$^{23}$Mg radiative proton capture: we aim at populating and study states in the $^{23}$Mg daughter nucleus following the β-decay of $^{23}$Al.




$$\omega\gamma \equiv \frac{2J_r+1}{(2J_p+1)(2J_t+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma_{tot}}$$

**Figure 5. Schematic correspondence of β-delayed proton-decay and resonant radiative proton capture.**

The selection rules allow that: s-wave radiative capture involves $J^\pi=5/2^+$ and $7/2^+$ states; beta-decay populates predominantly positive parity states with spins 3/2, 5/2 and 7/2. Figure 4 underlines that we need to locate the resonances and determine their properties (spin and parity and partial widths). Similar situations for other two proton capture reactions we studied through the decay of $^{27}$P and $^{31}$Cl, respectively. Measurements were done at the Cyclotron Institute of Texas A&M University using radioactive proton-rich nuclei produced and separated with the MARS recoil spectrometer. The short-lived radioactive species were produced in-flight (either $^{23}$Al, $^{27}$P, $^{31}$Cl, $^{20}$Mg etc., in most cases with purities 85% and up) and moving at 30-40 MeV/nucleon They were stopped and accumulated for about two lifetimes in a medium that was a detector (the implantation phase), then the beam was cut off and the protons from the β-delayed proton-decay were measured (the measurement phase). The detection medium was at first very thin silicon strip detectors (as thin as 65 and 45 μm) [39, 40], later a specially designed ionization chamber with micromegas gain amplifier [41]. While implanting the radioactive species in the very thin detectors mentioned above was an achievement per se because not only the RIB needed to be pure, but it needed to have a small spread of its incoming energy (not usual for those obtained from fragmentation or in-flight decay, but possible at MARS), the proton spectra in the region of interest (say 100-600 keV) were very much affected by the continuum background from the positrons emitted in the first step of the process [39]. The problem was more and more important toward lower proton energies, exactly those of interest in NA. Simultaneously, the proton-decay branching ratios become smaller at lower energies due to the barrier penetration factor in proton-decay. This overwhelming problem was diminished using gas as detection medium, as described in Ref. 41. The low amplitude signals from the decays in the detector that works in an ionizing chamber regime were then amplified with a micromegas systems of pads that also allowed for the diagnosis of the incoming beam of the implantation phase and the location of the decaying products in the second. Two devices ASTROBOX [41] and ASTROBOX2 [42] were realized and used in experiments with good results: beta- background free down to 80-100 keV and proton-decay branchings as low as $10^{-4}$ were obtained with these arrangements. We will skip the details in favor of sending the reader to the recent papers describing these experiments, the equipment and experimental methods involved, and their results. The method and the detection systems described can be used for other β-delayed charged-particle emission and worked even at radioactive beam rates of a few pps [43].

Recently a complex system based on same ideas was built at NSCL [44].

As a last point we want to stress what results from a careful inspection of the last equation shown in Fig. 4. The method allows for the identification of the location of resonances (Er) and for the determination of the proton and gamma decay branching, possibly of the spin and parity of the state(s), but does not allow the determination of the absolute value of the decay width(s) Γ, therefore of the evaluation of the absolute value of the resonance strength(s). The total decay width must be measured by other methods, for example by measuring the lifetime of the states through gamma-ray spectroscopy methods. This shows the complexity of the methods that must be used to get good nuclear data for NA.

## *5.Conclusions*

As stated in the Introduction, the indirect methods of nuclear physics for astrophysics briefly presented would not be useful as standalone in nuclear astrophysics but need to be included in the whole environment that the problem of the origin of energy and of the elements in the Universe encompasses. As such a number of other directions of research must be considered. Therefore, stellar dynamics, nucleosynthesis modeling, observations (space-based telescopes, cosmochemistry, etc.) must be considered as part of the discussions. Discussions that need to involve members of what were, and in cases still are, considered different branches of physics.

The present review of existing indirect methods in nuclear astrophysics included the list of accepted methods, pointing to some specifics for each. Only brief assessments of problems with the accuracy of each indirect method, experimental and theoretical, stressing the importance of calculated absolute values. At points we specified the need for modern theories and codes, of better systematics, of tests of validity and of the parameters to use in calculations. A thorough review of the existing experimental methods, equipment and specifics was not included here, as is beyond authors’ abilities. Similarly, the new facilities, including RIB facilities, and their nuclear astrophysics programs were not discussed in this paper.

We can only point to discussions at the workshop on related topics and new directions: discussion and attention should be given also to the contribution of excited states to the processes in stellar plasma (the topic of the talk by A. Petrovici, see Ref. 45 and references therein.

Nuclear reactions in laser induced plasmas is becoming a hot topic in the last few years and are bound to become increasingly important soon after the first measurements were made in the newly available petawatt lasers [46, 47]. We dare to say that in the future laser induced plasmas will offer ways to evaluate experimentally the contribution of the excited states to nuclear reaction rates in stars, while currently only theoretical predictions are being made [45].

The problem of the equation of state of nuclear matter, crucial for the connection between nuclear physics and neutron stars, was not attempted here (and at the workshop). Nor did have a large, thorough, coverage the problem of the structure of neutron-rich nuclei on the path of the r-process. There are and shall be topics for dedicated meetings and papers.

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# Nuclear Breakup and Coulomb Dissociation of $^{9}$C Nucleus Studied at RIBF RIKEN

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The $^{9}$C breakup was studied during the SAMURAI29R1 experiment through inclusive and exclusive measurements at energies around 160 AMeV for $^{9}C$, in order to evaluate the astrophysical $S_{18}$ factor for the inverse process $^{8}$B(p,$\gamma$)$^{9}$C at energies in the region of astrophysical interest. The radiative proton capture on $^{8}B$ is important in the hot $pp$ chains, in explosive Hydrogen burning ($ppIV$ and $rapI$), at temperatures between $0.05 < T_9 < 1K$, as possible alternative paths across the A=8 mass gap. Another goal of this experiment was a detailed study of the breakup reaction mechanism. During the experiment the nuclear breakup process was studied using a *natural C target* with 425 $\mu$m thickness and the Coulomb dissociation by using a *natural Pb target* with 150 $\mu$m thickness. The reaction products were tracked simultaneously using a system of position sensitive Si detectors and in total 1024 output channels were read out by using new dual gain preamplifiers (*DGP*) specially designed for the experiments of the HI-p collaboration.
The SAMURAI29R1 experiment was carried out during the SAMURAI 18Oxygen 2018 Spring campaign and it is part of the HI-p collaboration together with another three experiments.
Performances of the setup used and first results of the analysis are presented.

**KEYWORDS:** nuclear breakup, photodissociation, silicons, HINP

## 1. Introduction

The main motivation for studying the proton breakup reaction on $^9$C nucleus is the astrophysical impact of its inverse reaction, the radiative proton capture on $^8$B nucleus. The $^8$B(p,$\gamma$)$^9$C reaction was proposed [1] as a possible bypass of the $3\alpha$-process in low metallicity massive stars, in order to produce the fuel for the CNO cycles by a sequence of protons ($pp-III$ and $pp-IV$ in hot $pp$-chains of Hydrogen burning) and rapid alpha capture reactions ($rap-I$ branch) on nuclei close to the proton drip line.

The thermonuclear energies relevant for nuclear astrophysics are below the Coulomb barrier, where the reaction cross-sections are very small. To measure such cross-sections is even more complicated when radioactive nuclides are involved. In order to bypass the experimental difficulties inherent to the direct measurements, different indirect methods were implemented in nuclear astrophysics for measuring the capture cross-sections.

Another fact that leads to study the $^9$C breakup is the large spread of the experimental results for the determined astrophysical S-factor, obtained in the previous experiments [2].

## 2. Indirect methods in nuclear astrophysics

During the NP1412-SAMURAI29 experiment two indirect methods were used: nuclear breakup and Coulomb dissociation with the goal of performing inclusive and exclusive measurements of the breakup reaction cross-section of $^9$C nucleus in nuclear and Coulomb fields.

As it was already proved, the $^9$C has the last proton weakly bound and its breakup in a nuclear field is a strong peripheral process. From the momentum distributions and the absolute one proton removal cross-section, the Asymptotic Normalization Coefficient (ANC) of the radial wave function of the last nucleon will be extracted. The method was used successfully in the past to evaluate astrophysical S-factors for other reactions like: $^7$Be(p,$\gamma$)$^8$B, $^{22}$Mg(p,$\gamma$)$^{23}$Al,$^{23}$Al(p,$\gamma$)$^{24}$Si, all these are documented in Ref. [3–6]. During this experiment, for studying the nuclear breakup, it was used a natural C target of 425 $\mu$m thickness.

The Coulomb dissociation was proposed as an indirect method in nuclear astrophysics more than 30 years ago to evaluate the reaction cross-section for the radiative capture processes. The method proposes to measure the inverse reaction of the radiative capture in a field of virtual photons created by the fast projectile moving in the strong Coulomb field of a target ( [7,8]) with high atomic number $Z$, like the Pb target of 150 $\mu$m used during run measurements. In order to determine the radiative capture reaction cross-section, the Detailed Balance principle ( [7]) will be used and it will be necessary to disentangle the contribution of different multipoles to the reaction cross-section.

## 3. Experimental setup

The kinematically complete measurement for the breakup reaction of $^9$C was performed at RIBF in RIKEN by using the SAMURAI spectrometer. During the SAMURAI Oxygen18 Spring Campaign, all the experiments used as primary beam the neutron-rich $^{18}$O nucleus accelerated at 230 AMeV energy, by using in the last stage of the RI beam acceleration the SRC [9], with a beam intensity higher than 400 pnA. The proton-rich $^9$C secondary beam was obtained and separated by using the two-stages in-flight RI beam separator BigRIPS [9], where at the F0 focal plane the primary beam hit a 2mm thick Be target. Then, for a better separation of the secondary beam at F1 and F5 two Al degraders of 8 mm and respectively 2mm were placed. After these beam line systems, the secondary beam composition was: $^9$C - 87%, $^8$B - 2.9% and $^7$Be - 10%. For the beam PID measurement during the beam transportation along the BigRIPS line to the SAMURAI experimental area, two plastic scintillators at F3 and F7 with 3mm thickness were used.

The detection setup used to achieve the goals of the experiment, during the physics measurements, consisted of two parts: the standard SAMURAI detectors and a new Silicon strip detectors system placed between the target and SAMURAI spectrometer entrance. By using this detection configuration it was possible to perform inclusive and exclusive measurements of the $^{9}$C breakup. In the Fig. 1 the experimental setup is shown. The standard SAMURAI detectors used were, starting from the SAMURAI upstream area to the downstream side: two plastic scintillators for triggering, energy loss and timing (SBT1&2), two beam drift chambers for $^{9}$C position tracking (BDC1&2), two pairs of silicon GLAST detectors, a drift chamber (FDC0) used for space phase reconstruction of the resulting fragments, two arrays of plastic scintillators hodoscopes (HODF24 & HODP16) that were installed at the exit window of the SAMURAI spectrometer for measuring the time of flight and energy loss of the reaction products, and two drift chambers used to track the resulting protons (PDC1&2). As in all experiments of this campaign, the SAMURAI magnetic spectrometer was used to analyze the rigidity of the products, together with the detectors in order to reconstruct the momentum distributions of the beam and of the resulting fragments. The standard SAMURAI detectors are detailed in Ref. [10]. The production of the relatively clean proton-rich $^{9}$C secondary beam from neutron-rich $^{18}$O primary beam was the notable success of this experiment.

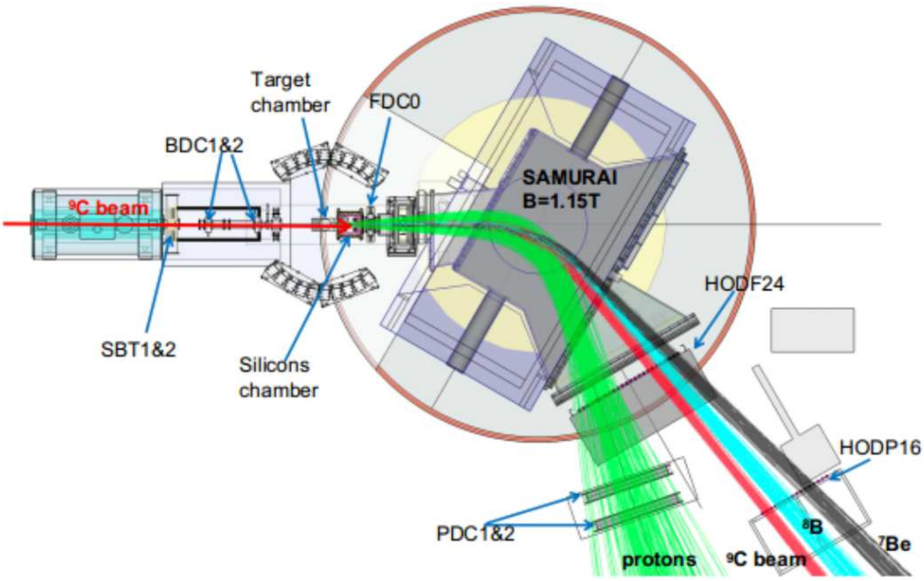


**Fig. 1.**: Top-view of the SAMURAI experimental hall. With the red, green, light blue and grey are drawn the trajectories of the $^{9}$C beam, protons and of the heavier fragments $^{8}$B and $^{7}$Be, respectively.

One of the novelties of this experiment was the system of 4 position sensitive silicon strip GLAST detectors and the associated electronics. Each of the silicon detector has 128 strips ($4x128 = 512strips$) and together with the new dual gain preamplifiers (DGP) assured the simultaneous tracking of the reaction products: protons and heavy cores. In this manner a total of 1024 output signals were detected and processed. This was possible due to the high dynamic range of the DGP, sensitive in the same time to the proton and fragments energy loss in the silicon detectors. By using the information obtained from the silicon detectors processed signals together with the HODF24 and PDCs signals it is possible to reconstruct the momentum of the produced protons. More details about the silicon system can be found in Ref. [11, 12]. In Fig. 2 can be observed that the combination of the two detection parts can distinguish between protons and the ligh nuclei simultaneously detected.

The data analysis results will be reported in a forthcoming paper.

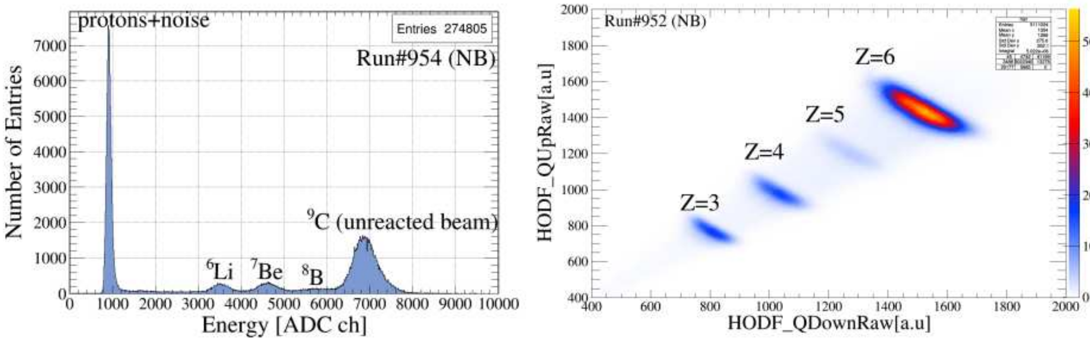


**Fig. 2.**: In the left part can be seen the reaction products signals in the silicon detectors, detecting simultaneously the nuclei with Z=1, Z=3, Z=4, Z=5 and Z=6. In the right side the same nuclei detected in the hodoscope HODF24

## 4. Conclusions

The experiment was successfully carried out. We have demonstrated the separation of the protons and fragments signals in the silicon detectors system and the possibility to reconstruct the trajectories using these complex exclusive measurements.

We observed the one and two protons removal channels on both intended targets and on other components of the setup (e.g first pair of the silicon detectors).

The combination between the breakup measurements in nuclear and Coulomb fields is being used because complementary information can be extracted. Thus the exclusive measurements intended to check the reaction mechanism and to improve the reliability of the nuclear astrophysics conclusions.

## 5. Acknowledgements


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# A study in using MICROMEGAS to improve particle identification with the TAMU-MDM focal plane detector

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ABSTRACT

A MICROMEGAS detection amplifier has been incorporated into the design of the TAMU-MDM focal plane detector with the purpose of improving the energy resolution and thus, the particle identification. Beam tests showed a factor of 2 improvement over the original design, from 10%–12% to 4%–6%, for ions with A≤40 at E/A ∼ 10–20 MeV.

## 1. Introduction

The Multipole–Dipole–Multipole (MDM) spectrometer at the Cyclotron Institute, Texas A & M University has been in use for over 25 years, since it was brought from the University of Oxford in 1992 [1] together with the focal plane detector [2,3]. Since then, numerous experiments have been performed with this beamline for giant resonance studies, as well as for astrophysical reaction rate studies, among others.

The MDM focal plane detector, also called the "Oxford detector", has been used in particular to study elastic scattering and transfer reactions for the determination of astrophysical reaction rates using the Asymptotic Normalization Coefficient (ANC) method [4–6]. The detector provided position information for raytrace reconstruction and energy loss signals for particle identification. For these experiments, it was important to be able to separate A and A+1 nuclei and the Oxford detector has done this successfully for particles with masses up to and including A = 22 [7]. A study of the reaction $^{13}$C($^{26}$Mg, $^{27}$Mg)$^{12}$C showed that this was at the limit of the detector, or beyond it, in terms of its particle identification (PID) capabilities.

This limitation sparked the idea of modifying the Oxford detector to increase its resolution in measuring energy loss. A contributing factor to this was also the ongoing facility upgrade at the Cyclotron Institute intended to provide unstable re-accelerated beams.

The idea of how to improve the energy resolution of the Oxford detector came from a previous study that involved building a detector for low-energy protons from beta-delayed proton decay. This instrument, called AstroBox [8], used Micromegas technology [9] to not only measure proton energies as low as ∼100 keV without being overwhelmed by the beta background, but as shown in Fig. 1, it was also able to detect heavier ions with very good separation for a good range of mass numbers.

Given the positive results obtained with AstroBox and the relatively easy operation of the Micromegas, it was decided that modifying the Oxford detector to include Micromegas for energy detection would be faster, less costly and with the potential to be more successful than any other option for an upgrade. Preliminary reports on this upgrade project can be read in [10] and [11].

## 2. The original detector

The Oxford focal plane detector is a gas-filled gridded ionization chamber with 4 resistive avalanche counters (ACs) and 3 aluminum anodes. These ACs are used to measure position at four depths inside the detector to determine the angle of the particle track for RAYTRACE [12] reconstruction. The anodes are used to determine the energy lost in the gas and are connected in a manner that gives 2 energy loss signals. Isobutane gas is used at pressures between 30 and 200 Torr, depending on the nuclei studied. A Frisch Grid (FG), along with fourteen electrodes (thin bars) going around the four sides, form a Faraday cage that ensures field uniformity inside the detection region [2]. Two photomultipliers (PM) are coupled to a plastic scintillator plate and attached to the back of the detection chamber. The scintillator is used to stop the nuclei and measure their residual energy. The PM signals are also used to trigger the data acquisition system [3].

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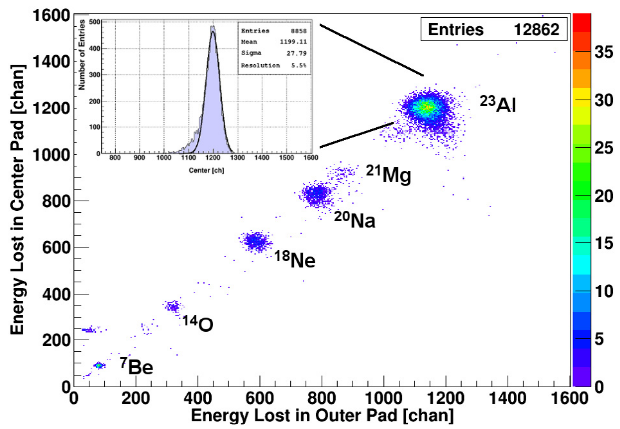



**Fig. 1.** 2-D histogram measured using AstroBox showing the energy losses of a $^{23}$Al beam and its contaminants. The plot gives energy loss in the central pad (Y axis) versus the energy loss detected by one of the outer pads (X axis). The insert represents a $Y$-axis projection of the $^{23}$Al data giving the energy resolution.

In summary, the Oxford detector provided 11 output signals: 8 for position determination, 2 for energy loss (called **dE1** and **dE2**) and one for the residual energy (label **PM**). The specific gas pressure and scintillator thickness, as well as the voltages on the various elements of the Oxford detector are chosen specifically for each experiment, with the goal of having the secondary beam particles of interest pass through the gas and stop in the scintillator and be detected with optimal resolution. In these circumstances, energy resolutions for **dE1** and **dE2** varied between 10% and 17% depending on gas pressure (the lower the pressure, the poorer the resolution). Additionally, **dE2** was consistently worse than **dE1** because the signal is smaller (shorter path of travel) and the straggling effect from the particle passing through the previous sections becomes more significant. Moreover, for gas pressures below 30 Torr, the **dE2** signal tends to have a significantly lower signal to noise ratio (S/N) making it unusable.

## 3. The MICROMEGAS upgrade

The upgrade of the Oxford detector was focused on improving the energy loss detection with Micromegas by obtaining relatively high gains and reaching a higher signal to noise ratio. The modified section of the focal plane detector consists of two regions. Particles pass through a drift gap (several cm across), causing ionization in the gas. The positive ions are collected by the cathode, while the electrons drift though the Frisch grid and enter the Micromegas. The electrons are focused through the stainless-steel mesh of the Micromegas with high efficiency and are subsequently amplified in the gap via an avalanche mechanism. With appropriate electric fields in the two regions, this technology has been shown to provide gains as high as $10^5$ [9]. In essence, the Micromegas component acts as an amplifier for the ionization signal created in the drift region.

The main concern about using this technology was that such a detection scheme, combining Micromegas with a gridded ionization chamber, had not been used before. A lesser concern was that our previous knowledge (see Ref. [8] on AstroBox) of operating the Micromegas lay close to the atmospheric pressure regime and not the low pressures ($\leq$ 200 Torr) needed for heavy ions in the Oxford detector.

Considering these initial unknowns, the upgrade had to be reversible. If the modifications were not successful, it was important for us to be able to revert to the original design without losing significant experimental time. The simplest method to achieve this was to replace the **dE2** anode (Fig. 2) with a Micromegas anode of identical geometry.

The new anode consists of a circuit board (labeled A in Fig. 3) printed with gold-plated copper anode pads (labeled B in Fig. 3). The PCB is 6 mm thick to give close to perfect planarity. Each pad is 32.5 mm deep (along the beam) and 44 mm wide (across the beam) giving a total of 28 pads (4 rows of 7 pads) and forming a detection area of 13.5 cm by 30.9 cm. Below the pads is a micromesh (labeled D in Fig. 3) made of stainless steel inter-woven wires with diameter of 18 μm and a pitch of 63 μm.

The electrons' transparency (95%) through the mesh [9] is attained by reaching an optimized field ratio between the drift and avalanche zones. Bias on the anode leads to a field ∼10 kV/cm and yields an avalanche amplification region in the gap of 256 μm. The mesh is supported at a uniform distance by resin pillars (labeled C in Fig. 3), with diameter of 0.3 mm and pitch of 5 mm. The 256-micron gap allows a relatively high gain at low pressures by giving the electrons a longer path to develop the avalanche. When the Micromegas is mounted on the Oxford detector plate, the mesh creates a drift gap with the cathode of 12 cm. Field uniformity in this region is ensured by the Oxford detector Faraday cage. Typical bias voltages are shown in Fig. 3. For the anode pads, the bias was varied for optimization.

Initially, we wanted a single large area of detection, like the previous **dE2** anode. However, in that case its capacitance would have been ∼2 nF, which would have reduced the signal to noise ratio. The current pad dimension is the largest that could be used while keeping a reasonable S/N ratio (∼300:1). Another concern was that the charge created by particles with high Z over the entire surface would be large, even at low voltages, and would trigger sparking and detector breakdown. These effects, although present, were rendered insignificant by appropriate tuning.

The 28 individual signals are routed through the internal circuit of the PCB to two DSub-25 connectors and from there to the vacuum-air feedthroughs. Two Mesytec MPR16 preamplifiers are directly connected to the feedthrough flanges in order to minimize noise. The shaping of the signals was done with 2 Mesytec MSCF16 modules and the data acquisition trigger was given by the PM signals.

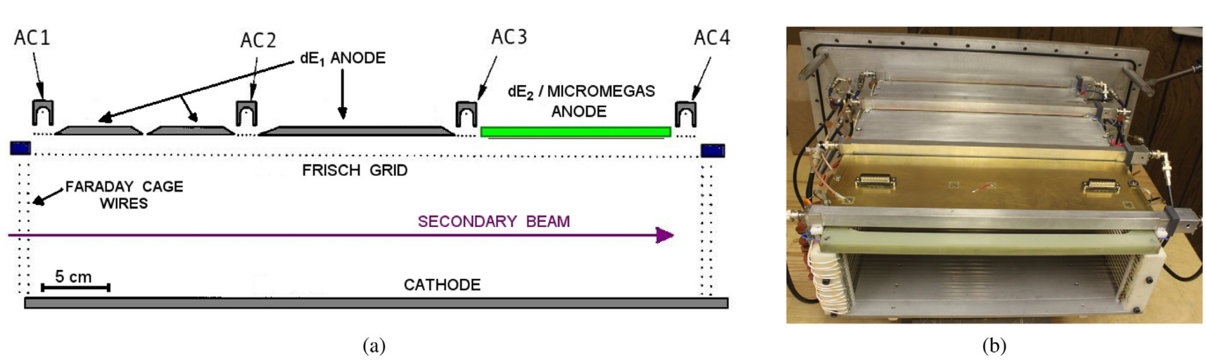



**Fig. 2.** (a) Schematic drawing of the inside components of the Oxford detector showing the position of the new Micromegas anode. (b) Photograph taken by authors showing the inside components of the Oxford detector and the mounted Micromegas anode.

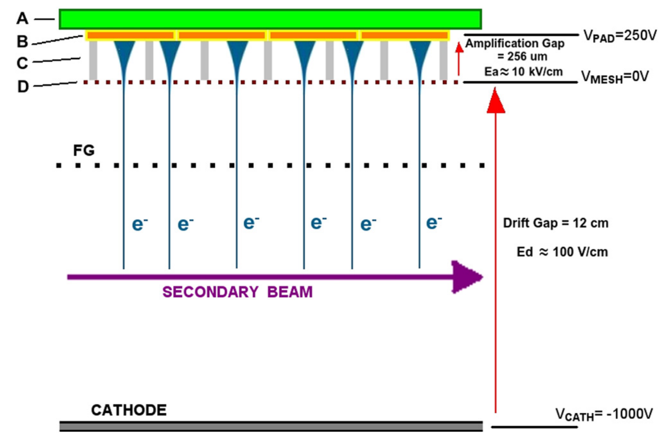



**Fig. 3.** Schematic of the Micromegas detector. Sizes are not to scale. Micromegas elements are labeled with capital letters: A-PCB, B-anode pads, C-insulating pillars and D-micromesh. The electron sheet is also indicated, in blue color and with 'e⁻'.

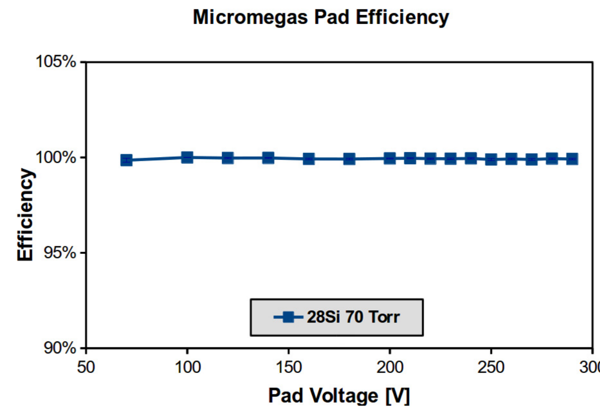



**Fig. 4.** Detection efficiency of pad R1–C4 as a function of pad bias voltage for $^{28}$Si particles in isobutane at 70 Torr. The $Y$-axis error bars indicate statistical uncertainties.

## 4. Tests and results

The Oxford detector upgrade was tested with a variety of beams. Specifically, there were 6 beams used: $^{16}$O, $^{22}$Ne, $^{26}$Mg, $^{27}$Al, $^{28}$Si and $^{32}$S. In each case, the beam energy was approximately 12 MeV/A. The gas choice of isobutane (> 99.95% purity) was not changed throughout the tests. The Micromegas element was the same throughout all the experiments, with a 256 μm gap.

To characterize the performance of the Micromegas, the elastically scattered beam was collimated with a narrow slit (0.1° wide). The Micromegas response was plotted in individual pad histograms containing the raw data. Throughout this paper, individual pads will be referred to according to their row and column, for ex. R1–C1 represents the pad in row 1 and column 1.

### 4.1. Efficiency

The detection efficiency was evaluated as the ratio between the counts recorded by the Micromegas pads and the counts detected by **dE1** (the ionization detection region of the Oxford detector). Noise related counts are excluded. This ratio can be seen as a relative efficiency since it depends on the performance of the **dE1** component of the Oxford detector. Fig. 4 shows the efficiency of pad R1–C4 as a function of the pad bias voltage for elastically scattered $^{28}$Si particles passing through isobutane at 70 Torr. It can be seen that the efficiency is close to 100% for the entire range of bias voltages. This evaluation was done for all 28 pads with similar results. The detection efficiency across the Micromegas anode was found to be between 99.5% and 100%.

### 4.2. Linearity

In order to observe the linearity of the Micromegas response, it was necessary to have different amounts of energy deposited in the gas. The method to study this characteristic involved using a $^{22}$Ne beam at 12 MeV/A on a $^{13}$C target (100 μg/cm$^2$). The result was a cocktail of reaction products, as can be seen in Fig. 5, (a), which shows a 2-D histogram with row 2 response on the $Y$-axis and stopping energy on the $X$-axis.

The gas pressure in this specific case was 30 Torr. The various reaction products are indicated in the figure. The circled events were separated with a software gate and fitted with Gaussian distributions. Those data were then plotted versus position in the focal plane. Ground states and specific excited states were then determined leading to an estimate of energy loss in MeV using TRIM [13]. In each case, the response of the Micromegas was also determined in channels by fitting the corresponding peaks. Fig. 5, (b) shows the estimated energy loss on the $Y$-axis and the response of Row 2 of the new anode on the $X$-axis. It can be seen that the Micromegas linearity is quite good across the investigated range (the normalized $\chi^2$ of the fit was $1.62 \cdot 10^{-4}$).

### 4.3. Gain

The gain of the Micromegas was determined relative to the Oxford ion chamber, i.e.

$$Gain = \frac{N_{\text{total electrons}}}{N_{\text{ionization electrons}}}, \tag{1}$$

where $N_{\text{ionization electrons}}$ represents the average number of electrons produced in the initial ionization process and was determined from the ratio between the energy lost in the gas and the average energy needed to produce an ion pair, $\frac{E[eV]}{w}$. This number represents a rough estimate as not all the energy loss produces ion-pairs. The average energy, $w$, for isobutane is ~23 eV/electron–ion pair [14] and takes into account the fact that some pairs recombine.

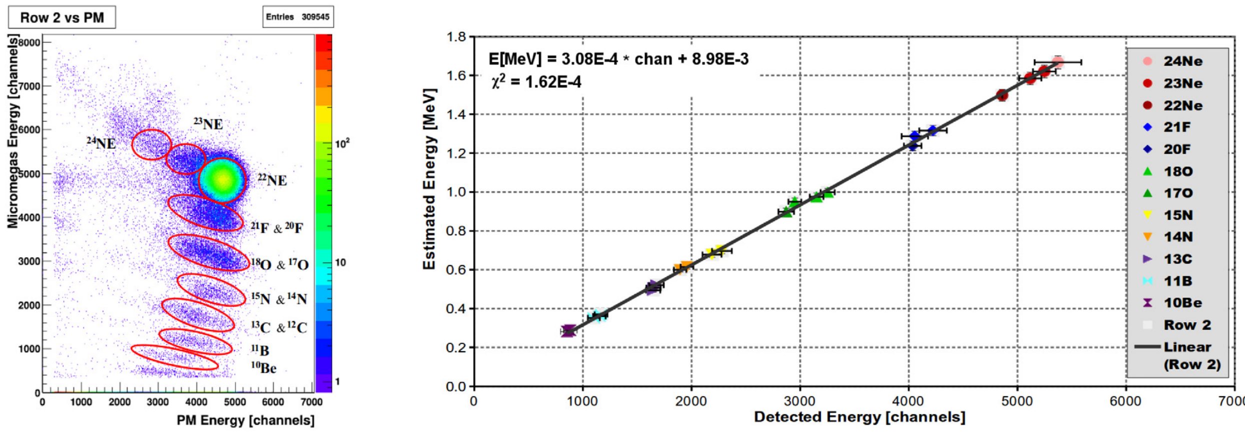
The total number of electrons, $N_{\text{total electrons}}$ collected by the Micromegas anode was defined as the ratio, $\frac{Q[\text{pad}]}{e}$, of the charge collected on each pad to the electron charge. To determine the charge Q we have used a calibration procedure that is not detailed herein (see Ref. [11]). The dependence on the amplification field was checked by changing the Micromegas anode bias, from 0 to $V_{max}$. The maximum voltage, $V_{max}$, that could be applied depended on the energy loss of the ionizing particle. Given a range of pad voltages of $V_{pad}$ = 100–300 V, amplification fields of up to 12 kV/cm were obtained without breakdown. In all cases, the ADC range limit was reached before the gas breakdown limit. Similarly, the gain variation with pressure and Z number of the ionizing particles were tested.

Each of the 6 beams was collimated with the narrow slit and elastically scattered off the $^{197}$Au target. The scattered beam was detected with the Micromegas and the resulting data are shown in Fig. 6.

The different colors of the curves indicate the pressure values, as noted in the figure caption. The trend indicates an increase in gain with decreasing pressure for the same amplification field. In addition, we found that data points taken at the same pressure fall approximately on the same curve, independent of the type of ionizing particle, which also agrees with expectations. While factors greater than $10^3$ are desirable in other cases, the gain results obtained in this work are high enough to ensure good signal to noise ratio for this application.

### 4.4. Energy resolution

Since the focus of this upgrade is the energy resolution, this was studied for different gain/bias voltages and gas pressures. We defined




(a) (b)

**Fig. 5.** (a) Micromegas row 2 energy versus residual energy for a $^{22}$Ne beam at 12 MeV/A at a pressure of 30 Torr. (b) Linearity plot for the total energy loss in Row 2. The $X$-axis error bars indicate statistical uncertainties. The $Y$-axis error bars indicate the uncertainty in the energy loss estimation.

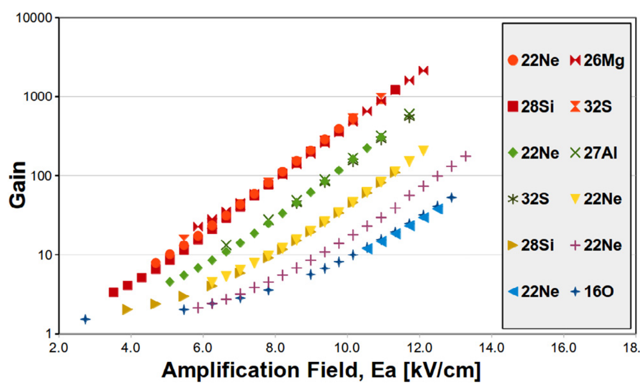



**Fig. 6.** Micromegas gain curves for all the ionizing particles used in the testing. The different gas pressures are color coded (Torr): red = 30, green = 50, yellow = 70, purple = 85 and blue = 100. The $Y$-axis error bars indicate statistical uncertainties but are too small to be visible.

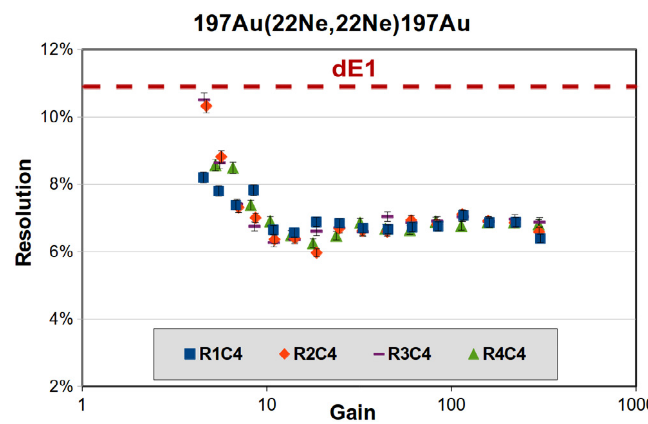



**Fig. 7.** Resolution variation with gain for the central pad in each row of the Micromegas anode, with a beam of $^{22}$Ne at 50 Torr pressure. The $Y$-axis error bars indicate statistical uncertainties. The red dashed line indicates the **dE1** resolution for this case, for comparison purposes.

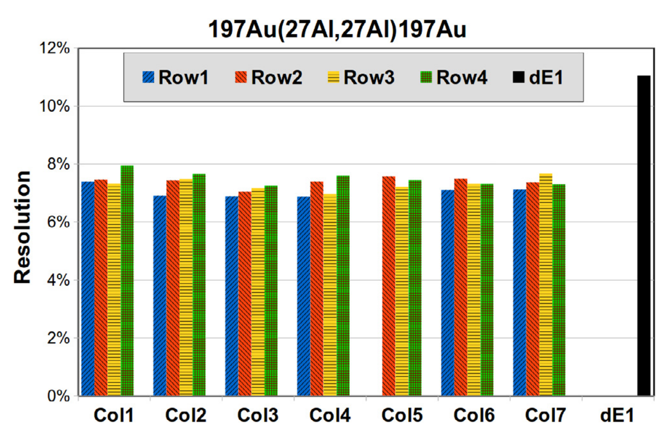



**Fig. 8.** Individual pad resolutions for$^{27}$Al at 50 Torr pressure. The solid black bar represents the **dE1** resolution for this beam and pressure and was added for comparison purposes.

the relative resolution for each pad as the FWHM of the energy loss peak. As an example, Fig. 7 shows the energy resolution variation with gain for the $^{22}$Ne beam, for 50 Torr pressure. The shape exhibits the threshold region between proportionality and amplification. From this figure, for this particular beam and pressure, the best setting to run at was with pad bias $V_{pad} = 260$ V (gain $\approx 150$), both in terms of resolution as well as signal strength.

The resolution variation across the Micromegas anode pads was also determined and can be seen in Fig. 8, for the case of $^{27}$Al nuclei and 50 Torr pressure. The pads in row 1 generally have better resolution then the ones in the other three rows. This is due to the fact that beam straggling is less in the gas region of that row than in the later ones. Straggling is also affected by gas pressure and Fig. 9 shows how the resolution of pad R1–C4 varies for the case of $^{22}$Ne, for 4 different pressures. As expected, the resolution worsens when the pressure decreases and the energy straggling increases.

For Micromegas, the overall range of values for the energy loss pad resolution, taking into account the different nuclei and settings is 5%–11%. This is to be compared to the **dE1** resolutions of 13%–20% for the original detector. Micromegas is definitely the better option.

## 5. Charge sharing

When the beam is tightly collimated, it is simple to make sure that only one column of pads detects the particles. Typically, for nuclear physics experiments with the MDM-Oxford, the collimation mask is much wider, specifically 4° wide (lab system). Additionally, the targets

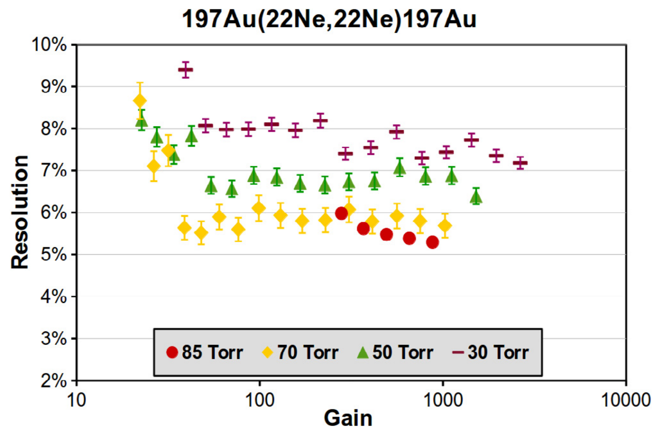



**Fig. 9.** Resolution variation with micromegas gain for pad R1–C4 for pressures of 85, 70, 50 and 30 Torr.

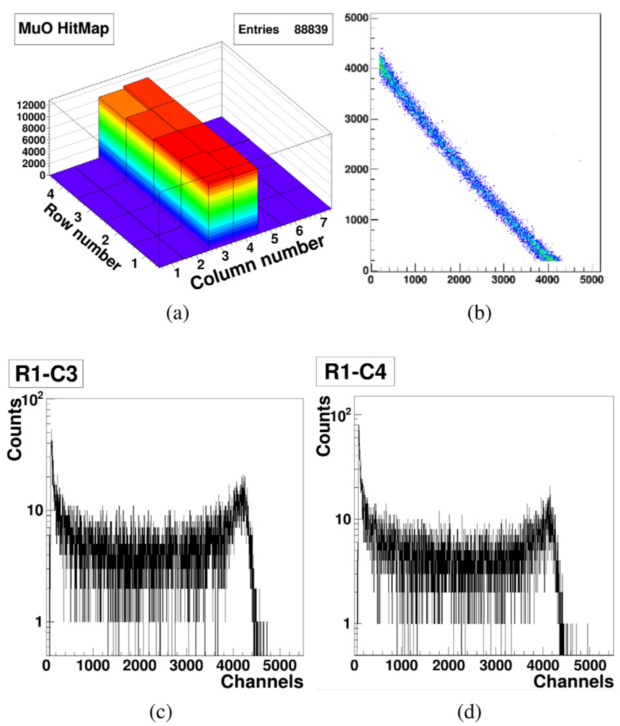



**Fig. 10.** (a) 3-D hitmap showing the path of the beam. (b) 2-D histogram showing data from R1–C3 on $Y$-axis and data from R1–C4 on $X$-axis. (c) Histogram showing raw data for pad R1–C3. (d) Histogram showing raw data for pad R1–C4.

used produce a variety of reaction products. As such, the particle paths cover the entire focal plane.

For the Micromegas anode, specifically, this means that often ionization occurs in such a way that the resulting avalanche curtain cloud can split between adjacent pads. Fig. 10 shows an example of charge sharing, where an elastically scattered pencil beam (1.6 mm wide at the entrance to the MDM spectrometer) of $^{22}$Ne particles was tuned through the gas region between columns 3 and 4. Histogram (c) is the 3-D hitmap of the Micromegas anode showing which pads detect a signal. Histogram (b) shows the charge sharing pads in the first row, with R1–C3 on the $Y$-axis and R1–C4 on the $X$-axis. The remaining histograms were placed next to their respective axes to show the individual pad responses.

In order to obtain an accurate measure of the energy loss of the ionizing particle, the amplified charge needs to be reconstructed properly

**Table 1**
Energy loss resolutions for different detection elements and for the different test beams used.

| Beam [Pressure in Torr] | $R_{dE1}$ [%] | $R_{Row}$ [%] | $R_{E_{Micromegas}}$ [%] |
|---|---|---|---|
| $^{16}$O [100] | 8.7 ± 0.3 | 5.3 ± 0.2 | 2.9 ± 0.1 |
| $^{22}$Ne [30] | 12.2 ± 0.3 | 7.4 ± 0.2 | 4.7 ± 0.1 |
| $^{22}$Ne [50] | 10.9 ± 0.2 | 6.6 ± 0.1 | 3.7 ± 0.1 |
| $^{22}$Ne [70] | 9.8 ± 0.2 | 5.6 ± 0.1 | 3.2 ± 0.1 |
| $^{22}$Ne [100] | 10.9 ± 0.2 | 6.5 ± 0.1 | 4.3 ± 0.1 |
| $^{26}$Mg [30] | 7.5 ± 0.1 | 7.7 ± 0.1 | 4.4 ± 0.1 |
| $^{27}$Al [50] | 5.3 ± 0.1 | 6.5 ± 0.1 | 4.0 ± 0.1 |
| $^{28}$Si [30] | 7.9 ± 0.1 | 8.8 ± 0.1 | 6.1 ± 0.1 |
| $^{28}$Si [70] | 6.1 ± 0.1 | 7.5 ± 0.1 | 4.9 ± 0.1 |
| $^{32}$S [30] | 14.9 ± 0.3 | 11.0 ± 0.2 | 6.9 ± 0.1 |
| $^{32}$S [50] | 7.9 ± 0.2 | 9.2 ± 0.2 | 5.6 ± 0.1 |

from these separate individual signals. However, there are two issues that complicate the reconstruction process. The first is that the gain may not be completely uniform across all the pads. The second problem is the danger of losing part of the signal in some cases. For example, if the charge sharing is largely uneven, it is possible that one part of the signal is so small as to register below the ADC or discriminator thresholds. In that case, the reconstructed signal amplitude is smaller than it should be and could lead to misinterpretation of the obtained data.

The non-uniformity issue was solved by gain-matching the pads. This procedure involves sweeping the beam across the anode. The tightly collimated beam loses approximately the same energy in each column and can be used to relate the pads to each other in each row. Any differences in path length due to the entrance angle into the detector are small enough to be negligible.

The second issue is more difficult to resolve. The biggest obstacle is the electronic noise. In order to reduce the amount of signal lost, the system noise must be as small as possible. Unfortunately, some of the noise contributions come from the elements in the beam-line, like the power supplies for the magnets and the vibrations caused by the vacuum cryo-pumps. It was not possible to fully isolate the detector from those noise sources.

However, if the noise can be minimized the effects of the lost data are less pronounced. Furthermore, for the purpose of particle identification the significant improvement in resolution compensates for these defects in reconstruction.

Taking these issues into account, an example of the quality or efficiency of the reconstruction process can be seen in Fig. 11. The top plots show the response of pads R1–C3 (resolution ≈ 6.2%) and R1–C4 (resolution ≈ 6.4%), when there is no charge sharing.

The bottom-left histogram, (c), shows the reconstructed peak when the beam passes between the two pads. As expected, the energy resolution is slightly worse, at 6.9%, and the peak exhibits a small tail on the high energy side. The bottom-right histogram, (d), shows the ionization chamber response, dE1, which is similar in shape but the resolution is significantly worse, at 11.4%. The number of counts under these two peaks differs by less than 0.1%.

As such, the reconstruction method was considered successful and was used in the following analysis and in later experiments.

## 6. Calculating the total anode energy loss

The first step in obtaining the total Micromegas anode energy loss is to gain-match the pads as explained above. The second step is to determine the multiplicity of an event for each row. Since a particle can either 'hit' one pad in a row or 'hit' between two neighboring pads in the same row, the multiplicity per row should only be 1 or 2 with adjacent pads. Events not satisfying these criteria for each row are considered non-physical. Under these circumstances, the energy detected by each row is determined from the sum of the individual,

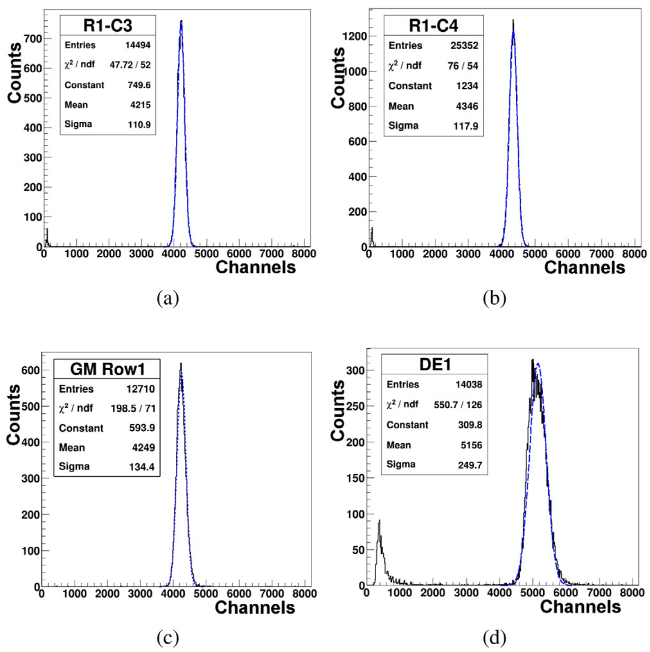



**Fig. 11.** (a,b) Energy histograms for pads R1–C3 and R1–C4. (c) Histogram showing the reconstructed energy. (d) Histogram showing dE1, the energy loss signal for the ionization chamber.

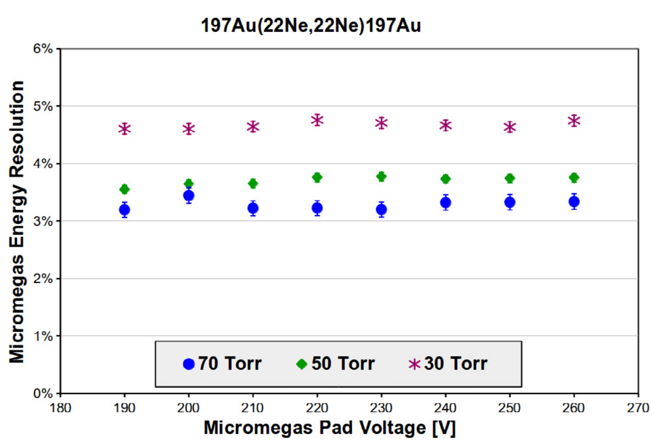



**Fig. 12.** Total energy resolution ($E_{Micromegas}$) for different Micromegas pad voltages and 3 different pressures (colors labeled in the legend) for $^{22}$Ne beam on Au target.

gain-matched, responses of the pads in each row. The final step in obtaining the total energy is to calculate the sum of the 4 rows.

During testing, several different methods were tried for 'summing' the 4 row energies. The sum of the gain-matched row energies produced a total resolution better by almost a factor of 2 than the single pad resolution. This can be easily understood from the fact that the initial number of electrons in all four cases (i.e. for each of the four rows) is roughly the same, therefore their sum is four times larger and correspondingly the relative resolution is $\sqrt{4} = 2$ times better, as it is dominated by statistics in the first stage (ionization). Averaging (arithmetic and geometric) was attempted as well and produced similar results to this sum.

A comparative analysis was done for all the scattered beams used as a function of pressure. The results are given in Table 1. The label $E_{Micromegas}$ represents the sum of the rows described above. The energy loss resolutions for **dE1** and the first Micromegas row are also given for comparison purposes.

It can be seen from Table 1 that given the relatively high gain coupled with a good signal to noise ratio, the upgrade allows a multi-sample of the energy loss that yields a significant improvement in the energy resolution. Fig. 12 shows the total Micromegas energy ($E_{Micromegas}$) resolution for different bias voltages and pressures. Comparing these with the numbers in Fig. 9 shows that the improvement in resolution by a factor of ~2 due to multi-sampling holds for a wide range of bias voltages. This in turn means that the choice of pad bias does not affect the total anode energy as much as it does individual pads, therefore allowing a larger optimal operational range for the Micromegas. Finally, Fig. 13 shows distinctly the difference between the ionization chamber and the Micromegas upgrade.

The two particle identification plots were recorded at the same time in identical conditions: cocktail products from the reaction $^{22}$Ne+$^{13}$C at a kinematic angular range of 7–11° lab and 30 Torr pressure in the Oxford detector.

## 7. Conclusions

We have introduced and studied an upgrade of the existing "Oxford detector" used in the focal plane of the MDM spectrometer at the Cyclotron Institute, Texas A&M University. The purpose was to enhance the resolution of the particle identification. The upgrade consists of a system of 4 rows x 7 columns = 28 pads with Micromegas technology to amplify the energy loss signal from the ionization chamber part of the gas detector. It was placed in the second half of the existing detector, while keeping the first part of it with the existing solution. We show herein that the Micromegas operates well even at the lower gas pressures (30–200 Torr), an important regime since the Oxford detector is used for heavy ions at moderate energies (10–20 MeV/nucleon), which require operation at these low pressures.

Up to now Micromegas were used at pressures around 1 atm. With moderate bias voltages of ~280 V, the Micromegas could be run to obtain energy loss resolutions 2 to 3 times better than the previous method, thus extending the particle identification capabilities well into the A = 40 region. We proved that the system remains linear for a wide range of energy losses, that inter-pad gaps lead to minor losses, however, the position reconstruction of the detector is not affected. While the increased number of pads complicates the acquisition and the analysis of the data (28 signals instead of one), the advantage is worthy and easily handled with today's technologies.

The modified detector was tested with count rates on the order of tens of kHz and found to be performing within the above stated parameters. A limit of 50 kHz was determined and attributed to the fragility of the wires used for the avalanche counters. The Micromegas component showed no problems with the increased rate. A separate study was performed on the performance of Micromegas as a function of rates and the extracted time resolution when compared with the PM.

Further improvement could come from padding the whole anode of the detector with Micromegas and using raytrace reconstruction in particle identification to allow comprehensive corrections which should improve even further the resolution. In our tests so far, such corrections were unnecessary as the differences in path length inside the Oxford detector were less than 1%. However, calculations show these differences increasing for heavier nuclei, higher reaction angles and increased acceptance of the detector.

## Acknowledgments

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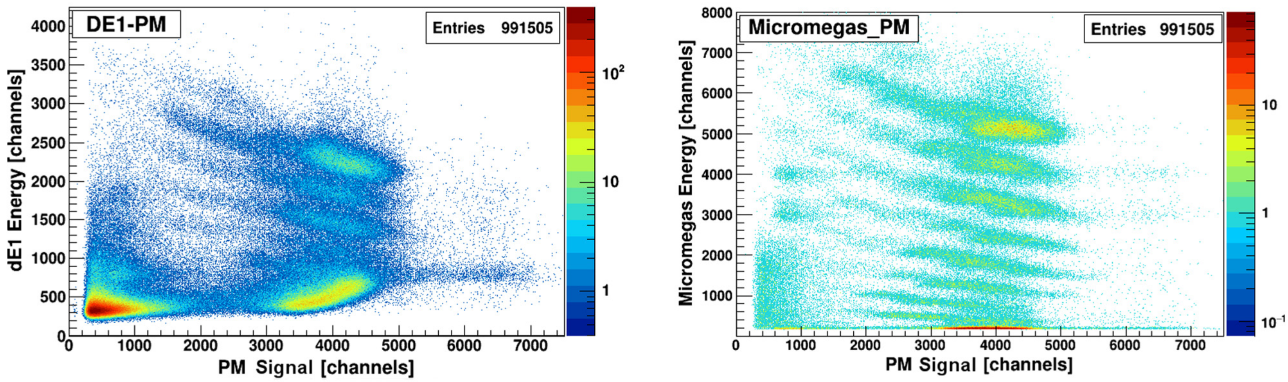


(a) (b)

**Fig. 13.** PID plots for the reaction $^{22}$Ne(12 MeV/A) + $^{13}$C at pressure = 30 Torr. (a) PID histogram representing the energy loss **dE1** versus residual energy. (b) PID histogram representing Micromegas energy loss versus same residual energy.

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**ANEXA 1.B Indicatori de realizare intermediară**

| Tip indicator | Număr | Scurtă descriere (dacă este cazul) |
|---|---|---|
| Număr de articole ştiinţifice în reviste şi volume indexate | 13 | 8 published + 5 submitted |
| Număr co-publicaţii | | |
| Număr articole publicate în top 10% cele mai citate publicaţii | 1 | 1 submitted |
| Număr de brevete obţinute la nivel naţional şi internaţional | - | |
| Număr de brevete în curs de obţinere la nivel naţional şi internaţional | - | |
| Numărul altor forme de DPI solicitate: desene, mărci în domeniul strategic. | - | |
| Număr de tehnologii elaborate/transferate | | |
| Număr de modele experimentale/prototitpuri | 1 | |
| Numărul de posturi de cercetatori echivalent normă întreagă (ENI) susţinute * | 6 | |
| Numărul de cercetători cu doctorat susţinuţi * | 3 | |
| Numărul de ingineri susţinuţi * | | |
| Numărul de tehnicieni susţinuţi * | | |
| Numărul personalului economic/administrativ susţinut * | 0,1 | |
| Numărul de doctoranzi susţinuţi * | 3 | |
| Număr de masteranzi susţinuţi * | | |
| Număr de conferinţe organizate * | 1 | |
| Număr de participări la Conferinţe Internaţionale* | 0 | |
| Număr de prezentări la Conferinţe Internaţionale | 9 | |
| Număr de postere prezentate la Conferinţe Internaţionale* | 0 | |
| Număr de participanţi la Workshopuri* | 6 | |
| Număr de prezentări orale la Workshopuri | 3 | |
| Număr de postere prezentate la Workshopuri | 3 | |
| Numarul participantilor la intruniri FAIR –din cadrul Colaborarilor (Collaboration Meetings) | 1 | |
| Numărul de proiecte Orizont 2020 (inclusiv cele ale partenerilor dacă este cazul) | 2 | |
| Numărul de evenimente de comunicare şi popularizare a ştiinţei susţinute * | 1 | |
| Număr de cursuri de instruire sau perfecţionare realizate | | |
| Altele (specificaţi) | | |

*) din Fondurile Programului

Bucharest-Magurele
Date: Nov. 28, 2019

Director de proiect,
Dr. Livius Trache

**PROCES VERBAL DE AVIZARE INTERNĂ A LUCRARILOR DE CERCETARE-DEZVOLTARE ŞI INOVARE (PVAI)**

Comisia de avizare constituită prin Decizia nr 494 / din 23.11.2016 luând în examinare lucrările efectuate de *Departamentul de Fizica Nucleara* la proiectul *„Nuclear Astrophysics with Indirect-methods and Rare Ion Beams/NAIRIB”* în cadrul etapei nr 3, care fac obiectul contractului nr. 02 FAIR / 16.09.2016 act adiţional nr.3/ 2017 încheiat cu *Institutul de Fizica Atomica –IFA,* a constatat următoarele:

a) Lucrările executate corespund clauzelor contractuale;

b) Toate documentele necesare efectuării plăţii există şi sunt corect întocmite;

c) Concluziile lucrării, principalele rezultate obţinute şi datele privind efectuarea cheltuielilor sunt prezentate în Raportul intermediar de activitate şi în documentele sale însoţitoare;

d) Planificarea activităţilor şi resurselor aferente realizării etapei următoare de derulare a proiectului, prezentată în Raportul intermediar de activitate, este corespunzătoare realizării obiectivului propus şi în concordanţă cu prevederile contractului;

e) Cota de cofinanţare realizată în faza de execuţie curentă este de……0…lei.

Comisia avizează **FAVORABIL** lucrările şi documentele şi consideră că pot fi prezentate pentru evaluare la Institutul de Fizică Atomică – IFA.

**COMISIA DE AVIZARE**

| Funcţia în comisie | Nume şi prenume | Semnătura |
|---|---|---|
| **Preşedinte** | Dr. Borcea Catalin | |
| **Membri** (cel puţin trei specialişti) | Dr. Stanoiu Alexandru | |
| | Dr. Mihai Constantin | |
| | Dr. Raduta Adriana | |
| **Secretar** | Dr. Livius Trache | |

## RAPORT EXPLICATIV AL CHELTUIELILOR

**1. Devizul postcalcul al etapei (DP) – ANEXA 2.A**

**2. Fişa de evidenţă a cheltuielilor (FEC) – ANEXA 2.B**

**3. Fişa de evidenţă analitică postcalcul (FEAP) – ANEXA 2.C**